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LOW-TEMPERATURE ADDITIVE PERFORMANCE IN JET A FUELS

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University of Dayton Research Institute

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Interim Report

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1.0 EXECUTIVE SUMMARY

The use of the low temperature (LT) flowability improving additive developed in the JP-8+100 LT program was studied for use in Jet A fuels. One major goal of the current program was to determine if this LT additive can be employed in Jet A fuel (with a specification freeze point of -40 °C) to improve the low temperature flowability to be equivalent to the flowability of JP-8 fuel (with a specification freeze point of -47 °C). The program commenced in November 2010, and this final report covers the period November 2010 to June 2012. The LT additive works by interacting with large normal alkane species which normally crystallize at temperatures below the fuel freeze point (FP), preventing these species from creating a matrix which entraps the bulk of the liquid fuel causing the fuel to become unflowable. The additive has been previously shown to be effective in JP-8 fuel for use in replacing JP-TS for the U-2 aircraft and for high-altitude, long-duration missions of the Global Hawk aircraft.

The following studies were performed: (1) fuel specification testing to show the effect of the additive on fuel properties; (2) additive concentration optimization in Jet A fuels and fuel surrogates via kinematic viscosity, dynamic viscosity, and scanning Brookfield viscosity measurements; (3) an aging study to determine deterioration of the additive during ambient temperature storage over a period of 4 years; (4) thermal stability studies using the quartz crystal microbalance to determine the effect of the additive on the deposit tendency of the fuel; (5) evaluation of the use of the LT additive in auxiliary power unit (APU) cold start situations; (6) small-scale icing simulator studies; and (7) static and dynamic crystallization visualization and flow studies.

The results indicate the LT additive does improve the flowability of near specification maximum FP Jet A fuels (near -40 °C) when employed at a concentration of 2,000 mg/L to a flowability equivalent to near specification maximum FP JP-8 fuels (near -47 °C). The additive increases flowability not by changing the fuel FP, but rather by allowing the fuel to remain flowable by preventing the formation of large crystals which form a matrix which entraps the mostly liquid fuel. Viscosity measurements demonstrated that the LT additive increases the fuel viscosity at temperatures above incipient fuel crystallization, where the fuel remains a liquid. This viscosity increase is likely due to the large, high molecular weight oligomeric structure of the additive. Jet A fuels exhibit higher average low temperature liquid-phase viscosity than JP-8 fuels and the further increase due to the LT additive can place some Jet A fuel viscosities above the low temperature viscosity guidelines for proper nozzle atomization used by engine OEM's.

The specification evaluation (performed at 2,000 and 4,000 mg/L in two fuels) showed that most Jet A fuel properties are unaffected by addition of the LT additive except for: (1) failure of the appearance evaluation in one fuel; (2) an abnormal JFTOT result in one fuel; (3) failure of the total acid number test at the higher additive concentration; (4) an abnormal JFTOT deposit failure in one fuel; (5) failure of the existent gum evaluation; (6) and failure of the water reaction and WSIM evaluations.

The QCM thermal stability evaluation showed that the additive decreased deposition in all three fuels evaluated. In one of the fuels the presence of the additive resulted in an interesting

temporary change in fuel density/viscosity properties during oxidation. This interesting observation is unlikely to cause thermal stability or fuel property issues during aircraft operation.

The APU analysis demonstrated the unique cold relight and atomization requirements of these engines. High altitude, long duration operation of some APUs may provide a severe environment for Jet A LT fuel due to the need for relight after long, cold soak periods without fuel heat sources prior to the fuel injector. In addition, some of these APUs contain very fine filters which may not pass the small crystals that are produced in the presence of the LT additive. Further studies would need to be performed to evaluate specific APU/aircraft systems to allow complete confidence in the performance of Jet A LT fuels in this environment.

The additive aging study showed no detrimental degradation of the additive after 4 years of ambient temperature storage. The aged additive was evaluated via dynamic viscosity and no difference in performance in allowing fuel flow was observed between the aged additive and fresh additive.

The small-scale icing study confirmed that the additive improves the LT flowability of Jet A fuel down to -47 °C in studies of fuel flow through B52 fuel filter material. Additional studies of flow and static visualization were performed to determine the mechanism by which additized fuel flow inhibition occurs through filters. The data appear to show that flow inhibition through filters primarily occurs due to the increase in fuel viscosity with reducing temperature, rather than because of fuel crystals plugging filter media. Further visualization work would be needed to confirm this observation.

It is recommended that further work be performed before the LT additive is fielded for use in Jet A fuel. In particular, the effect of the increased fuel viscosity at liquid fuel temperatures needs to be evaluated in the particular aircraft/engine platform being employed. The effect of this increased viscosity on fuel atomization in the engine combustor is likely dependent on the engine employed and the fuel flow schedule of the aircraft. In addition, observations of combustor liner coking at high additive concentrations during the previous U-2 and Global Hawk studies, emphasizes the need for combustor testing of the additive at the optimized use concentration in the engine system of interest. Thus, identification of the aircraft system or systems for which the LT additive may be required for operation with Jet A fuel is needed.

2.0 INTRODUCTION

The purpose of this program was to study the feasibility of using the LT flowability improving additive developed in the JP-8+100 LT program for use in Jet A fuels. One major goal of the current program is to determine if this LT additive can be employed in Jet A fuel (with a specification FP of $-40\text{ }^{\circ}\text{C}$) to improve the LT flowability to be equivalent to the flowability of JP-8 fuel (with a specification FP of $-47\text{ }^{\circ}\text{C}$). The program commenced in November 2010, and this final report covers the period November 2010 to June 2012. The originally proposed program consisted of four major tasks including: (1) Additive Optimization for Jet A Fuel Studies; (2) Small-Scale Icing Simulator Studies; (3) Specification and Thermal Stability Studies; and (4) Additive Combustion Studies.

Here we studied the use of the LT flowability improving additive developed in the JP-8+100 LT program for use in Jet A fuels. This relatively high molecular weight oligomer is added at a concentration of 4,000 mg/L when used for improving the flowability of JP-8 fuels to JP-TS conditions and 2000 mg/L when addressing Global Hawk extreme temperature missions. One benefit of the proposed conversion of USAF CONUS operations to Jet A fuel, is the cost savings of acquisition for Jet A vs. JP-8 fuel. As the additive is used at a relatively high concentrations, its cost is high and would overwhelm any cost savings due to Jet A conversion. As such, the additive is expected to only be used on aircraft and/or missions for which the LT flowability is absolutely required, and would be injected at the skin of the aircraft. The requirement for the additive would need to be determined based on modeling of the fuel tank temperatures for each mission. A current study in support of the Jet A base conversion demo, funded by AFPET, is being performed by AFRL to evaluate fuel temperatures during actual missions for B-52, B-1, KC-135, and F-15 aircraft platforms. This study can be used to feed fuel temperature information into the current additive study to determine the conditions (e.g., temperature) for which the additive is required. A previous study found that C-17, C-130, and C-5 missions that required the use of the additive with Jet A fuels were very infrequent (Ervin et al., 2010).

2.1 Additive Background

It is important to understand that the low temperature flowability improving additive in the JP-8+100 LT package acts by decreasing the size and changing the morphology of the n-alkane crystals that form upon cooling. In doing so, it prevents the formation of large, leaf-like crystals which encapsulate liquid fuel forming a matrix of two-phase material (liquid and solid) which readily plugs filters and prevents fuel flow. The additive does not lower the freeze point of the fuel and does not prevent the fuel from freezing. Rather, it encourages the small amount of large n-alkane species that freeze ($<1\%$ of the fuel) to form small, needle-like crystals that stay suspended in the liquid fuel. At temperatures below the freeze point of the fuel, this two-phase suspension appears as a milky, cloudy liquid-fuel phase, but it retains good flowability. It should also be recognized that many in the aviation industry have recommended that a flowability test replace the freeze point test as a measure of low temperature fuel performance.

In addition, as a two-phase suspension is expected for temperatures below the fuel FP, the small crystals that do form need to pass unimpeded through the fuel system until the fuel is heated, via transit through pumps and heat exchangers, above its freeze point. In the original additive

development program, a U-2 fuel system simulator was constructed with actual aircraft components, such as a strainer, float control valve, dual control valve, and transfer pump. The intent of these simulator studies was to determine that the two-phase fuel suspension that forms below the fuel FP would retain adequate flowability to feed the engine properly. In addition, it was important to determine that the wax crystals that form are small enough to flow through the close tolerance components present in the fuel system.

In addition to the evaluation of cold flow improving ability of the additive, the previous program evaluated the effect of the additive on various specification properties and other fit-for-purpose properties such as materials compatibility, combustion, turbine hot-section materials compatibility, additive-additive compatibility, filtration-coalescer compatibility, and altitude relight. Many of these evaluations are still valid for Jet A fuels. In the present study we have performed evaluations of the use of the low temperature flow improving additive required for Jet-A-fuel-specific usage.

Thus, we proposed the following series of laboratory tests to provide an initial evaluation of the efficacy of using the cold flow improving additive developed for the JP-8+100 LT additive package in Jet A fuels: (1) Scanning Brookfield Viscometry studies of the effect of Jet A sample and additive concentration on low temperature flowability; (2) small-scale fuel freezing simulation studies of the effect of wax crystal formation on fuel flowability through filters; (3) evaluation of the combustibility of optimized levels of LT additive in Jet A fuels.

2.2 Additive Optimization for Jet A Fuel Studies

As mentioned previously, the low temperature improving additive in the JP-8+100 LT package was developed for use in the U-2 aircraft, and was optimized for use in JP-8 fuel. The goal of its development was to improve the LT flowability of JP-8 fuel (with a specification FP of -47 °C) to be equivalent to the flowability of JP-TS fuel (with a specification FP of -53 °C). The goal of the current program was to determine if this low temperature additive can be employed in Jet A fuel (with a specification FP of -40 °C) to improve the LT flowability to be equivalent to the flowability of JP-8 fuel. As the base fuel and temperature range are different from the original additive application, studies needed to be performed to determine the efficacy of the additive in Jet A fuel in improving the flowability over the temperature range -40 to -47 °C. This entailed study of a range of fuels and additive concentrations in screening tests of low temperature flowability, such as the Scanning Brookfield Viscometer.

The Scanning Brookfield Viscometer consists of a fuel sample contained in a temperature controlled bath with a rotating spindle suspended in the fuel. A viscometer head monitors the torque required to maintain a constant spindle velocity, which is converted to a viscosity. As the bath temperature is slowly decreased the fuel viscosity is constantly monitored. Large, sudden increases in viscosity are noted when fuel flowability is inhibited. The technique has been used to screen the cold flow improving capabilities of a large number of candidate additives in the JP-8+100 LT program. Comparison of additive performance using this method was found to compare favorably with other more expensive and time consuming laboratory and small-scale methods.

2.3 Small-Scale Icing Simulator Studies

Our previous studies determined that the LT additized JP-8 fuel would perform well in the U-2 fuel system. But, use of the low temperature additive in Jet A fuel needs to be evaluated in any aircraft platforms in which it would be employed. Rather than performing expensive and time consuming flowability tests in all candidate aircraft platforms, one option is to select a single aircraft platform, or small number (e.g., two or three) of aircraft platforms, that represent worst-case conditions for additive use. One aircraft platform that may represent worst-case conditions is the B-52 bomber, which flies high altitude missions for which the outside air temperatures can be very low ($<-80^{\circ}\text{C}$ outside air temperature). The long duration missions of the B-52 are ideal for allowing long heat transfer times which provides maximum cooling of the aircraft fuel. Further studies would need to be performed to properly assess the utility of a particular platform as a worst-case. Once a worst-case platform (or platforms) is determined, the particular problematic components, such as filters, valves, and controls can be evaluated using the Small-Scale Icing Simulator (SSIS) for the ability of wax crystals to flow through these components.

A small-scale icing simulator (SSIS) was designed for studies of the icing of water in fuel lines for use in the fuel system icing inhibitor (FSII) studies. Fuel is continuously circulated in a closed loop through an aircraft filter component, while the temperature is slowly decreased to the fuel freeze point via a heat exchanger and environmental chamber. In the FSII studies, water is added to the fuel and icing is monitored via delta pressure measurements across the filter and flow changes. The system will be used in the current program by employing water free fuel and cooling below the fuel FP. The ability of the wax crystals that form to flow through the filter or other component can then be readily monitored as a function of fuel sample, temperature, cooling rate, and additive concentration. Fuel crystallization has also previously been monitored and visualized in a small glass wing system which could also be employed for these studies.

In the current study the SSIS system was modified for study of fuel crystallization and flowability as detailed in the icing simulator section below.

2.4 Specification and Thermal Stability Studies

Any change to fuel composition can affect the wide variety of carefully controlled fuel specification properties. We have performed specification tests to monitor these properties in various Jet A fuels. Previous work with the low temperature improving additive showed that the high concentration and molecular weight of the additive caused failures in existent gum specification evaluations (ASTM D381). The existent gum evaluation is contained in the specification to monitor fuel degradation during production and storage. The specification failures obtained after LT additization are not due to fuel degradation, but rather are expected with a high molecular weight, non-volatile additive. Combustion studies described below can determine the combustibility of the additive and thus the existent gum test failure should not be an issue for engine operation. Another important fuel property that needs to be carefully monitored is thermal stability. Thermal stability can be strongly affected by small amounts of reactive species. We have performed quantitative measurements of the effect of the additive on Jet A thermal stability via the Quartz Crystal Microbalance technique using a range of Jet A samples. In addition, the storage stability of the LT additive was evaluated by comparing the performance of existing supplies of the additive with a fresh batch manufactured for this program by the LT additive manufacturer (GE Betz).

2.5 Additive Combustion Studies

One of the primary challenges in development of the JP-8+100LT additive package was in combustion of the fuel/additive mixture. For use as a JP-TS substitute, a relatively high concentration was required to provide the desired low temperature flow properties. The relatively high molecular weight and high concentration of this additive was found to cause combustor liner coking issues under some combustion conditions. An optimized concentration of 4,000 mg/L was found to minimize combustor coking issues for the U-2 aircraft while still retaining the required low temperature flow improvement. For the Global Hawk a lower optimum concentration of 2,000 mg/L was necessary due to a greater tendency for combustor coking in the AE 3007 engine. The effective concentration for improving the low temperature flowability of Jet A fuel may be different than the previous studies, so combustion coking evaluations may need to be performed. A T63 helicopter engine is available at AFRL for such testing and was used in the previous U-2 and Global Hawk studies involving JP-8 +100LT additive. These experiments would offer visual demonstration of the collection of any unburned additive or undesirable accumulation of combustion products on the fuel nozzles and combustor canister. The nozzle and canister images collected from experiments with Jet A LT would be compared to those obtained using Jet A, JP-8, and JP-8+100. However, the ability of the fuel-additive mixture to be adequately dispersed and burned with a desirable spray pattern will ultimately depend on the fuel nozzles and combustor air flow in the actual platform. Thus, combustor sector and engine tests would eventually need to be performed.

As detailed below, challenges in employing the JP-8+100LT additive in Jet A fuels were encountered during the current study. Further inquiries into these issues precluded the commencement of the combustion studies planned in the original study proposal. Future work in approving the additive for use in Jet A fuels will require combustion studies to be performed that are relevant to the aircraft/engine platform of interest.

3.0 RESULTS AND DISCUSSION

3.1 Specification Testing

Jet A specification testing was performed for two Jet A fuel samples (POSF-2926 and POSF-3602) with two levels of the LT additive: 2,000 and 4,000 mg/L. The results are shown in the Table 1. The table shows that each of the samples failed the FSII and conductivity evaluations. These failures were expected as none of the fuels contained FSII or static dissipating additive. In addition, the POSF-3602 fuel failed the MIL-STD-3004C Appearance evaluation when treated with the LT additive due to visual particulate. We are not sure of the cause of this result, but this is not a required ASTM D1655 test and thus is not a failure.

Both fuels failed the TAN evaluation when treated at 4,000 mg/L, but not at 2,000 mg/L. This TAN failure at high LT additive levels was noted in the previous LT additive qualification, and is due to the presence of a weak acid component in the additive. The current intent is to employ the additive at the lower concentration (2,000 mg/L), so the failure at 4,000 mg/L should not be a problem.

Fuel POSF-3602 shows a JFTOT failure at 2,000 mg/L due to an abnormal deposit, but passes at the higher concentration. All of the treated fuels show failure in the existent gum test due to the fact that the additive is a high molecular, non-volatile oligomer. In the previous LT qualification work, it was suggested that the existent gum evaluation be performed only before treatment with the LT additive.

Fuel POSF-2926 shows failures in the WSIM evaluation for both concentrations of the LT additive. Fuel POSF-3602 was not evaluated in the WSIM test. In addition, the additive shows failures in the water reaction evaluation for both fuels. The water reaction evaluation is a JP-8 requirement, but is not in the ASTM D1655 Jet A specification. The cause of the WSIM and water reaction failures has not been further explored in this study.

Table 1. Results of Specification Testing

Specification Test	ASTM D1655 - 11b Spec Requirement	Fuel 2926 Jet A	Fuel 2926 +7450 @ 2000 mg/L	Fuel 2926 +7450 @ 4000 mg/L	Fuel 3602 Jet A	Fuel 3602 +7450 @ 2000 mg/L	Fuel 3602 +7450 @ 4000 mg/L
Appearance		Pass	Fail*	Fail*	Pass	Pass	Pass
Total Acid Number, mg KOH/g	≤0.10	0.01	0.10	0.20*	0.00	0.10	0.20*
Aromatics, vol %	≤25	18	17	15	24	24	24
Mercaptan Sulfur, % mass	≤0.003	0.000	0.000	0.000	0.000	0.000	0.000
Total Sulfur, % mass	≤0.3	0.08	0.08	0.08	0.02	0.02	0.21
Distillation:							
10% recovered, °C	≤205	182	182	182	183	183	180
20% recovered, °C		189	189	189	191	191	190
50% recovered, °C		211	211	211	210	210	211
90% recovered, °C		250	249	250	240	241	242
EP, °C	≤300	267	266	267	265	263	268
Residue, % vol	≤1.5	1.2	0.8	0.9	1.1	1.0	0.9
Loss, % vol	≤1.5	0.3	0.1	0.6	0	0.4	0.5

*Value outside specification limit

NA = Not Analyzed

Table 1 (cont.). Results of Specification Testing

Specification Test	ASTM D1655 - 11b Spec Requirement	Fuel 2926 Jet A	Fuel 7671 (2926 +7450 @ 2000 mg/L)	Fuel 7672 (2926 +7450 @ 4000 mg/L)	Fuel 3602 Jet A	Fuel 7682 (3602 +7450 @ 2000 mg/L)	Fuel 7683 (3602 +7450 @ 4000 mg/L)
Flash point, °C	≥38	52	51	51	51	50	50
Freeze Point, °C	≤-40	-43	-43	-42	-54	-54	-55
Viscosity @ -20°C, cSt	≤8.0	5.2	5.2	5.4	5	5.2	5.3
Heat of Combustion (calculated), MJ/kg	≥42.8	43.2	43.3	43.3	43.0	43.0	42.9
Smoke Point, mm	≥25 or ≥18 w/	25	25	25	20	20	19
Naphthalenes, vol %	≤3	NA	NA	NA	0.9	0.9	0.9
Copper Strip Corrosion	≤1	1a	1a	1a	1a	1a	1a
Thermal Stability @ 260°C :							
Tube Deposit Rating	≤3	1	1	1	2	1A*	1
Change in Pressure, mm Hg	≤25	0	0	0	0	0	0
Existent Gum, mg/100mL	≤7.0	1	111*	245*	1	109*	251*
WSIM	≥70	92	0*	0*	81	NA	NA
Water Reaction	≤1b	1b	2*	2*	1	2*	1b
Conductivity, pS/m	50 to 600	0*	12*	26*	0*	0*	26*
Density, kg/L @ 15°C	0.775 - 0.840	0.807	0.807	0.808	0.820	0.820	0.82
Lubricity (BOCLE), wear scar mm		0.55	NA	NA	0.67	0.65	0.66
FSII (% vol)	0.10 – 0.15 (JP-8 spec)	0.00	0.00	0.00	0.00	NA	NA

*Value outside specification limit

NA = Not Analyzed

3.2 QCM Thermal Stability Studies

A quartz crystal microbalance (QCM) apparatus was used to assess the thermal stability characteristics of three Jet A fuel samples (POSF-2926, POSF-3219, and POSF-3602) with varying amounts of LT additive (POSF-7450). This apparatus has been used extensively to study the effects of additives on the thermal stability of jet fuels and has been previously described in detail (Zabarnick and Grinstead, 1994; Zabarnick, 1994; Zabarnick and Mick, 1999). The experiment was conducted by placing 60 mL of sample into a batch reactor. The sample was air saturated under room conditions, then closed and heated to 140 °C. Measurements of headspace oxygen, temperature, pressure, and mass accumulation were recorded, while the sample was reacted isothermally for 15 hours. These experimental conditions were chosen to highlight the differences in oxidation and deposition tendencies of various jet fuel samples due to differences in chemical composition. The objective of the current experiments was to determine if the LT additive has any negative effects on jet fuel thermal stability, i.e., a “no-harm” condition.

Table 2 lists the mass accumulation at 15 hours of thermal stress duration, and Figures 1 to 3 show the headspace oxygen and mass accumulation profiles for the three Jet A fuel samples with and without LT additive. These data show that addition of the LT additive resulted in a significant decrease in mass accumulation for all three Jet A fuels under all concentrations reported. Figure 2 shows an abnormal mass accumulation profile for POSF-3602 when the LT additive was present at both 2,000 mg/L and 4,000 mg/L. The mass accumulation, in both cases, appears to increase to a maximum then decrease to almost no deposit. Further investigation revealed that the crystal resistance (not shown), which is proportional to the square root of fluid density and viscosity product, i.e., $[\rho\mu]^{1/2}$, changed a proportional amount during this time, and therefore, the temporary spike in mass accumulation is, at least in part, due to a change in fluid properties around the crystal and not hard surface deposit. Regardless, the LT additive demonstrated no-harm to jet fuel thermal stability for all three Jet A fuels under the current experimental conditions for active additive concentrations of 1,000, 2,000, and 4,000 mg/L. Furthermore, the LT additive appeared to reduce surface deposition; however, in at least one instance thermal stressing of the fuel with LT additive appeared to affect fluid properties, which may impact fuel flow and/or atomization of the fuel under certain situations.

Table 2. QCM Deposition at 140°C

Jet A	LT Additive [POSF-7450] Concentration (mg/L)	Mass Accumulation at 15 Hours ($\mu\text{g}/\text{cm}^2$)
POSF-2926	0	3.5
	1,000	0.1
	2,000	0
	4,000	0
POSF-3602	0	2.9
	2,000	0.2
	4,000	0.1
POSF-3219	0	1.7
	2,000	0

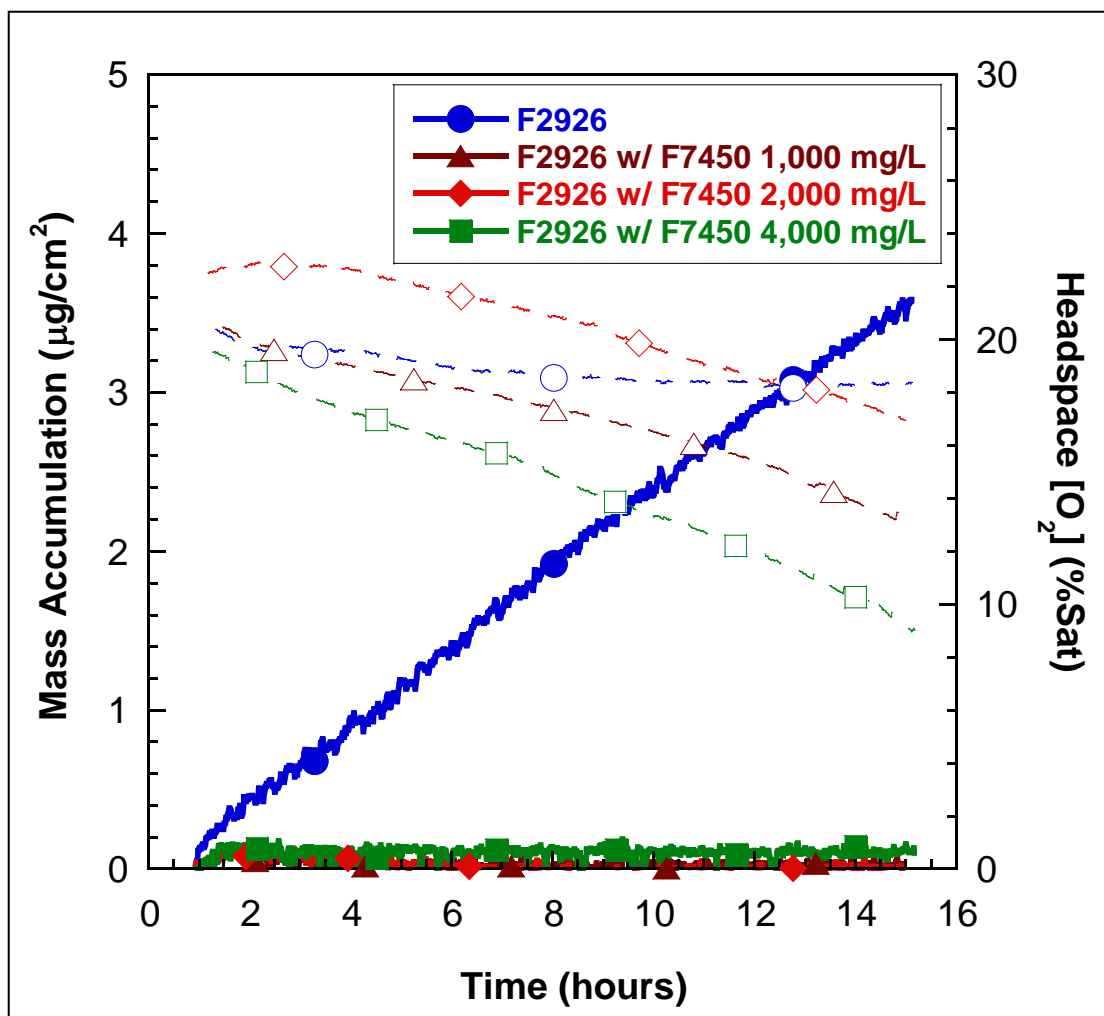


Figure 1. QCM Mass Accumulation and Headspace Oxygen Profiles

Closed markers and solid curves indicate mass accumulation, and open markers and dashed curves indicate headspace oxygen for Jet A fuel POSF-2926 with respect to LT additive (POSF-7450) concentration at 140 °C

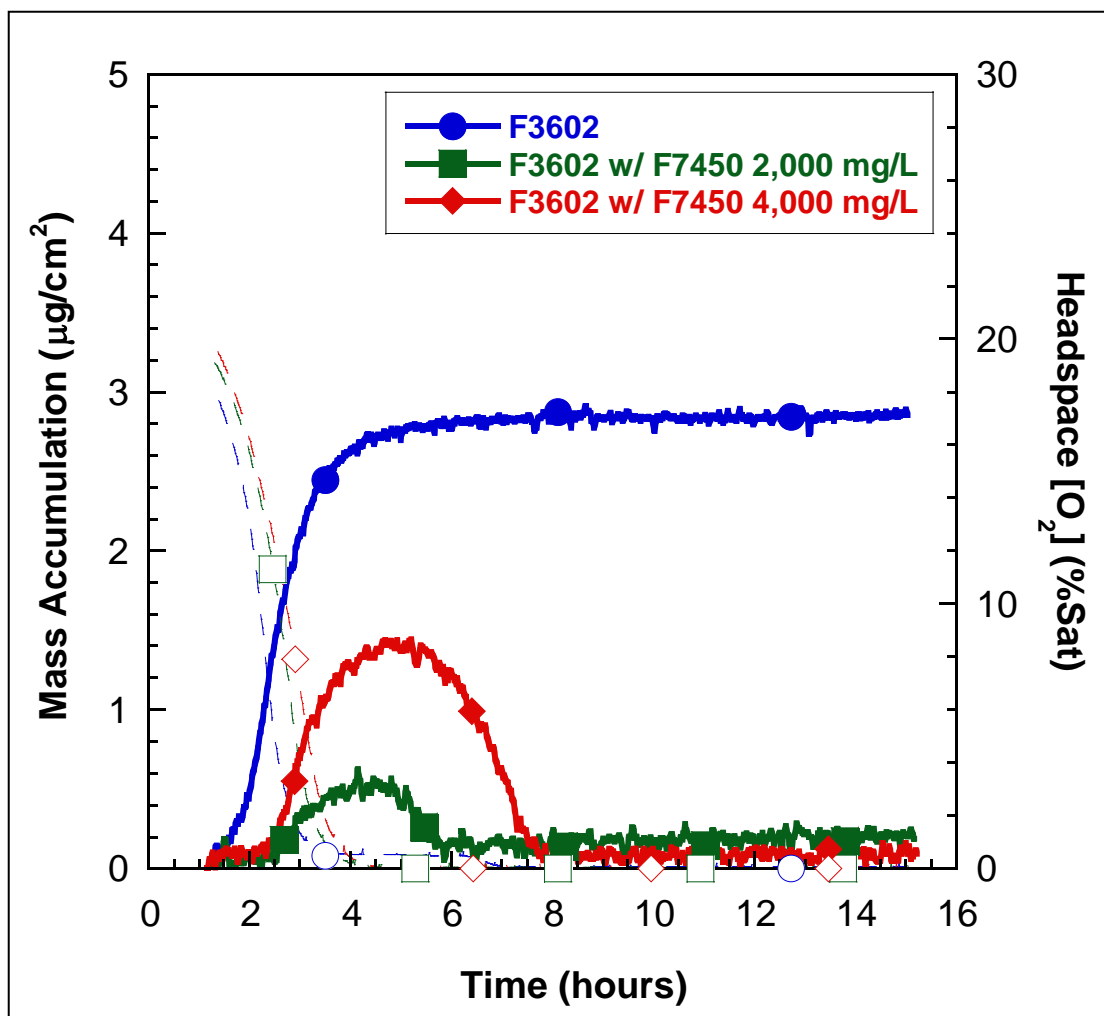


Figure 2. QCM Mass Accumulation and Headspace Oxygen Profiles

Closed markers and solid curves indicate mass accumulation, and open markers and dashed curves indicate headspace oxygen profiles for Jet A fuel POSF-3602 with respect to LT additive (POSF-7450) concentration at 140 °C

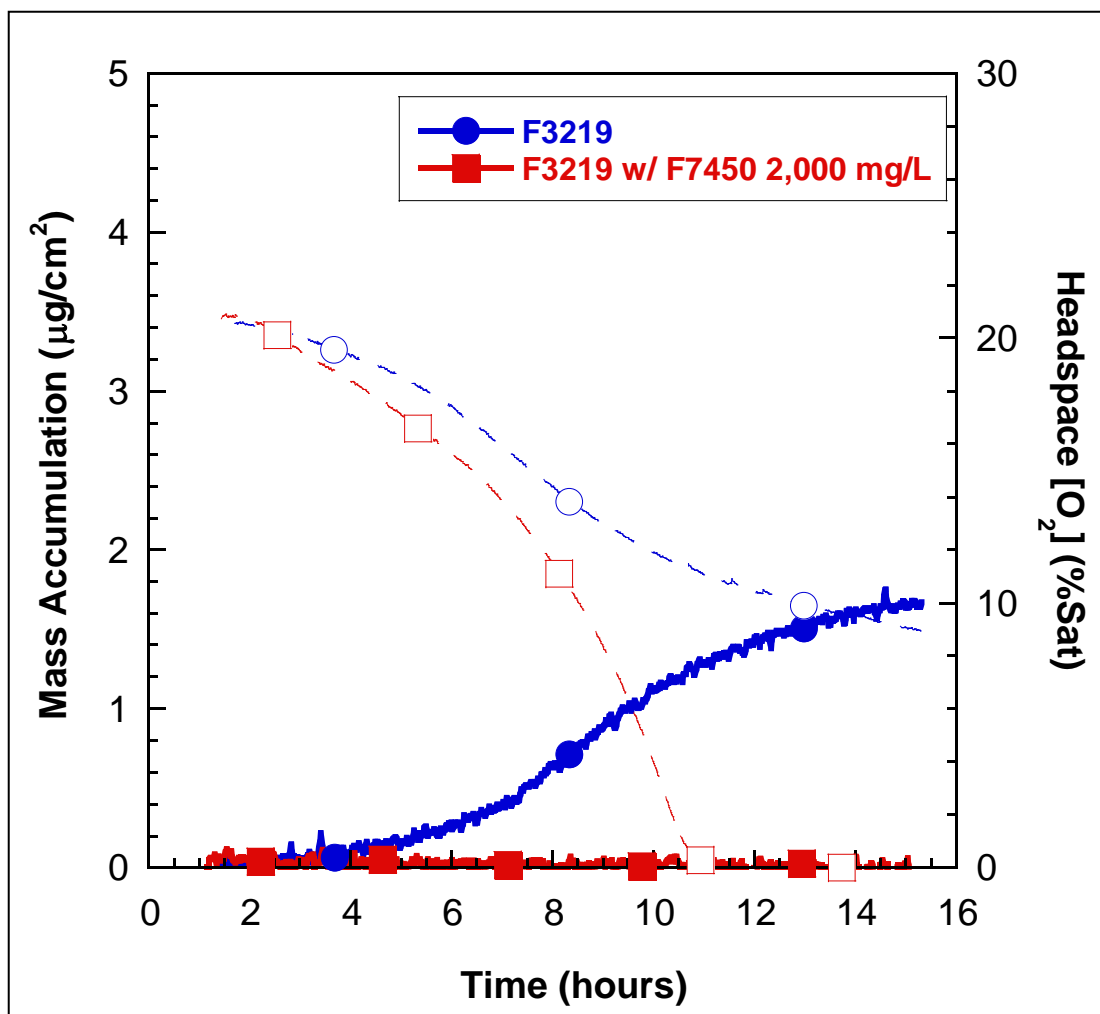


Figure 3. QCM Mass Accumulation and Headspace Oxygen Profiles

Closed markers and solid curves indicate mass accumulation and open markers and dashed curves indicate headspace oxygen profiles for Jet A fuel POSF-3219 with respect to LT additive (POSF-7450) concentration at 140 °C

3.3 Additive Optimization for Jet A Fuel Studies

The Additive Optimization for Jet A Fuel Studies Task commenced with identifying baseline fuels for the additive studies. In addition, work was performed to try to produce a worst-case (-40 °C FP) baseline fuel via the use of a surrogate fuel or fuel blending. Three currently available Jet A fuels and a surrogate fuel (Exxsol D80) were chosen as possible candidates initially because of their FPs.

In order to compare the LT viscosity behaviors of the fuels, they were studied using scanning Brookfield viscometry. In this technique, a stationary sample container (stator) containing the fuel sample and a metal rotor suspended in the center of the sample were connected to a viscometer head. The stator and rotor were lowered into a temperature-programmable methanol bath. The head provided the torque to the rotor to maintain it at a constant velocity as the temperature in the bath was lowered from -20 to -70 °C at a rate of 5 °C per hour. The torque

readings, along with the corresponding bath temperatures, were relayed from the head to the computer program.

The viscometer torque vs. viscosity behavior was calibrated with a mineral oil standard having known viscosities (in centipoise units, cP) at five temperatures from –20 to –45 °C. The calibration was accomplished by first obtaining the slope, m , and intercept, b , of the relationship between viscosity (η) and temperature (T) from the MacCoull, Walther, Wright equation as follows:

$$\log[\log(\eta + 0.7)] = m(\log T) + b \quad (1)$$

Then the torque of the mineral oil was measured at temperatures from –20 to –45 °C using the viscometer, and a bath cooling rate of 2°C per hour. The viscosity was calculated at each temperature and a linear relationship between torque and viscosity was generated. The slope and intercept of this linear relationship was used to convert torque measurements to viscosity measurements for fuel samples. Dynamic viscosity curves could then be generated of viscosity (cP) versus temperature (°C).

While the dynamic viscosity curves give accurate indications of the relative behavior of fuels over a range of temperatures, kinematic viscosity in centistokes (cSt) units is the current standard for evaluating fuel viscosity at particular temperatures. Kinematic viscosity measurements at –40 °C (ASTM D445) were used to anchor the dynamic viscosity measurements so that fuel viscosities could be compared between the two techniques. To convert between the dynamic and kinematic viscosity measurements it is essential to have accurate measurements of fuel density. Thus, density measurements of each of the fuels were performed at –40 °C using a pycnometer. The pycnometer is a specially designed glass sample container of a calibrated volume.

Figure 4 shows scanning Brookfield viscometer plots of viscosity vs. temperature for the four candidate baseline fuels for the additive optimization studies. The figure legend shows the measured FPs of these fuels; while the sudden increase in viscosity upon cooling (viscosity knee) indicates the temperature at which fuel crystallization begins. The plots show that fuel crystallization begins at temperatures 2 to 5 degrees lower than the fuel freeze point, which is obtained upon fuel heating. As Jet A fuel is refined to meet the –40 °C freeze point specification maximum, the normal maximum FP will be –42 to –43 °C as the refiners want a 2 to 3 degree margin to assure that the fuel will meet the specification. The fuel-like solvent, Exxsol D80, shows the “worst-case” behavior, exhibiting a FP of –40 °C and a fuel crystallization temperature of –42.6 °C. Thus we considered employing Exxsol D80 in the concentration optimization study, although it was not a real fuel, and displayed higher low-temperature viscosity behavior. One or two of the three Jet A fuels would also be employed.

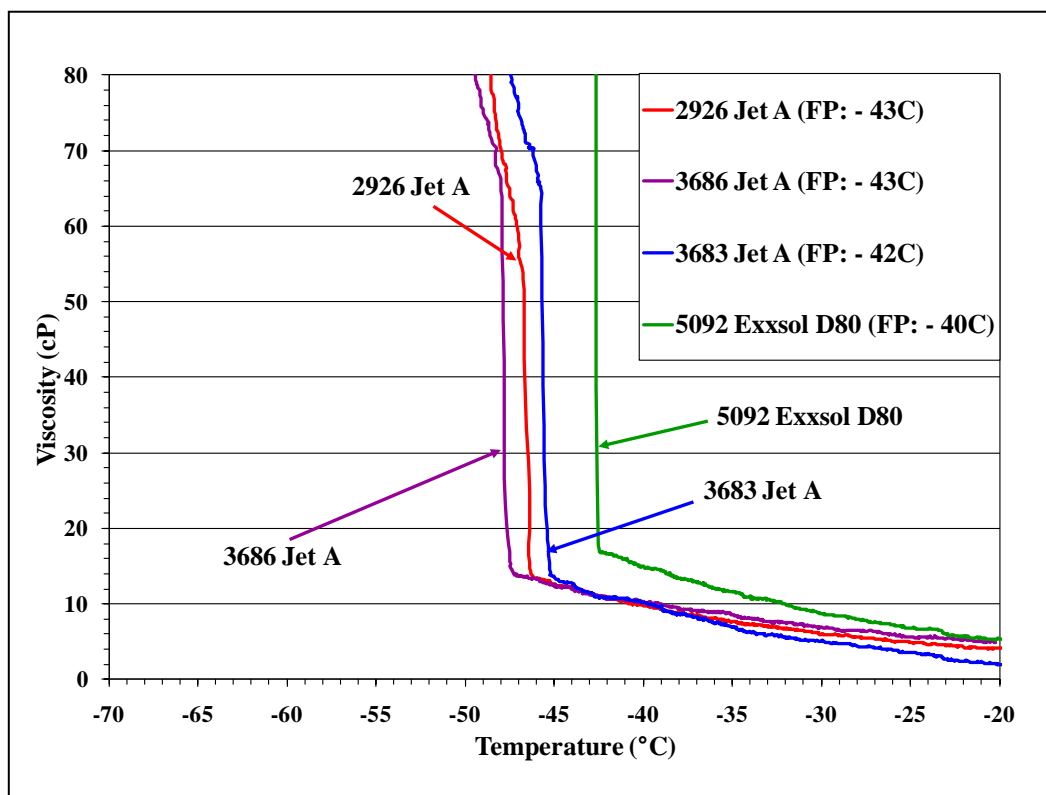


Figure 4. Scanning Brookfield viscometer data for three relatively high freeze point Jet A fuels and Exxsol D80

As an alternative to using the Exxsol D80, we also performed studies of fuel blending to determine the efficacy of creating a worst-case -40°C FP Jet A fuel by addition of small quantities of another fuel or solvent. Figure 5 shows viscometry results for the addition of small quantities (4 to 8 percent) of diesel fuel to a Jet A fuel. The plots indicated that the diesel fuel addition did increase the temperature of crystallization, but the diesel component appeared to be crystallizing separately from the jet fuel species at some concentrations. This was apparent from the shoulder in the viscosity curve, which developed near -40°C for the 92/8-percent case. The 96/4-percent case did not show a shoulder, and the diesel fuel does increase the crystallization temperature by $\sim 2^{\circ}\text{C}$; however, the overall behavior upon blending with diesel fuel was not ideal. Thus, other blending possibilities were explored.

Figure 6 shows results of viscometry runs for blends of Jet A fuel with varying amounts of Norpar 13 solvent. The Norpar solvent consists of n-alkanes centered around C13. As this solvent is lighter than diesel fuel, higher blend levels were required to obtain increased crystallization temperatures. The figure shows that a 5 % addition of Norpar 13 increased the crystallization temperature by approximately 4 degrees to -42°C , as in the Exxsol D80 solvent. It also had a freeze point at the specification maximum (-40°C).

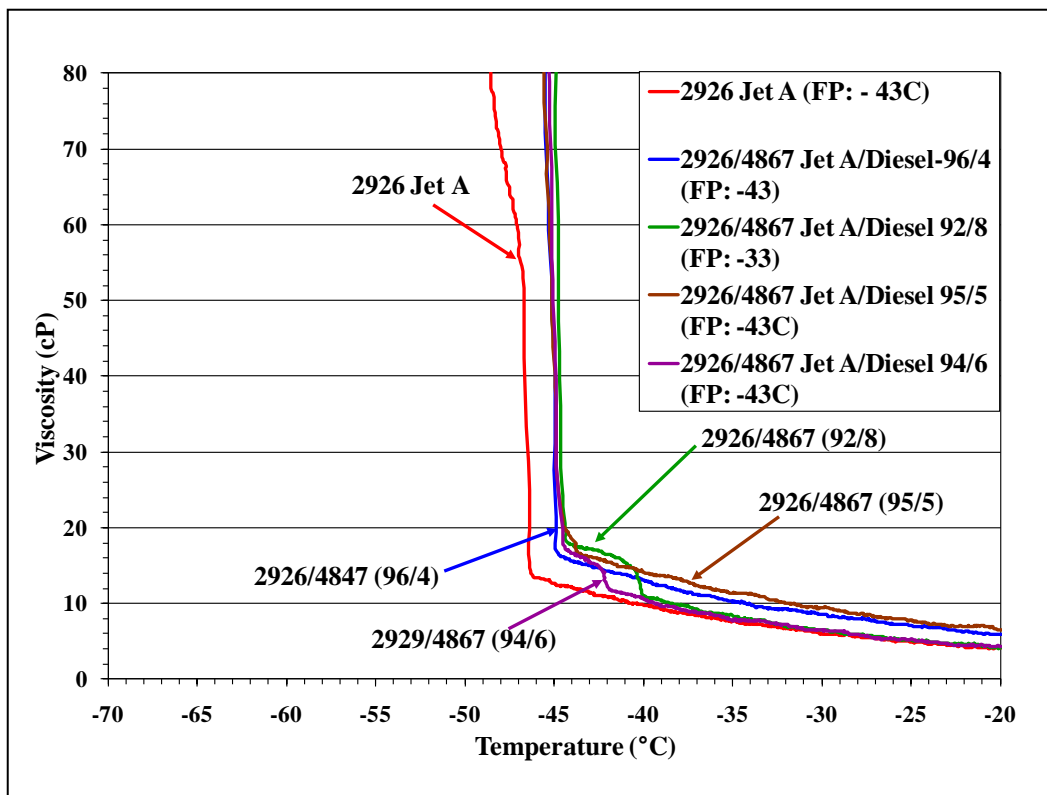


Figure 5. Scanning Brookfield viscometer plots for blends of Jet A fuel with varying amounts of diesel fuel

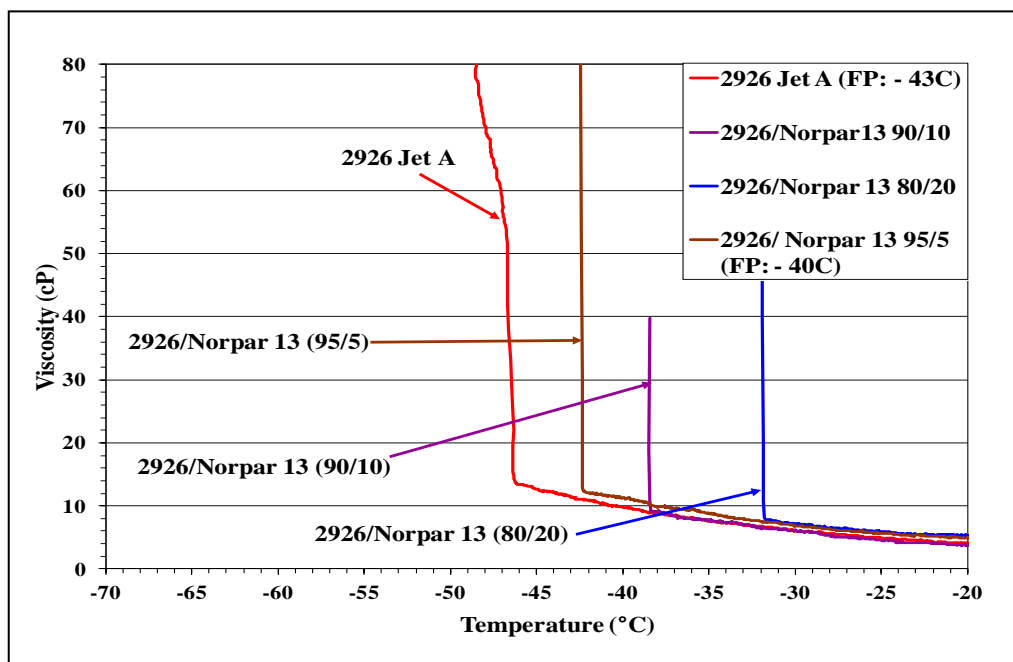


Figure 6. Scanning Brookfield viscometer plots for blends of Jet A fuel with varying amounts of Norpar 13 solvent

Through further investigation of fuel/surrogate blends, it was discovered that a blend of Jet A fuel POSF-2926 with 7% Exxsol D110 also yielded a fuel with a freeze point of -40°C . Although it exhibited higher low-temperature viscosity behavior than the Jet A/Norpar 13 blend (Figure 7), it most closely resembled a Jet A fuel. Therefore, it was chosen as the “worst-case” test of the LT additive (POSF-7450) and assigned POSF number 7463.

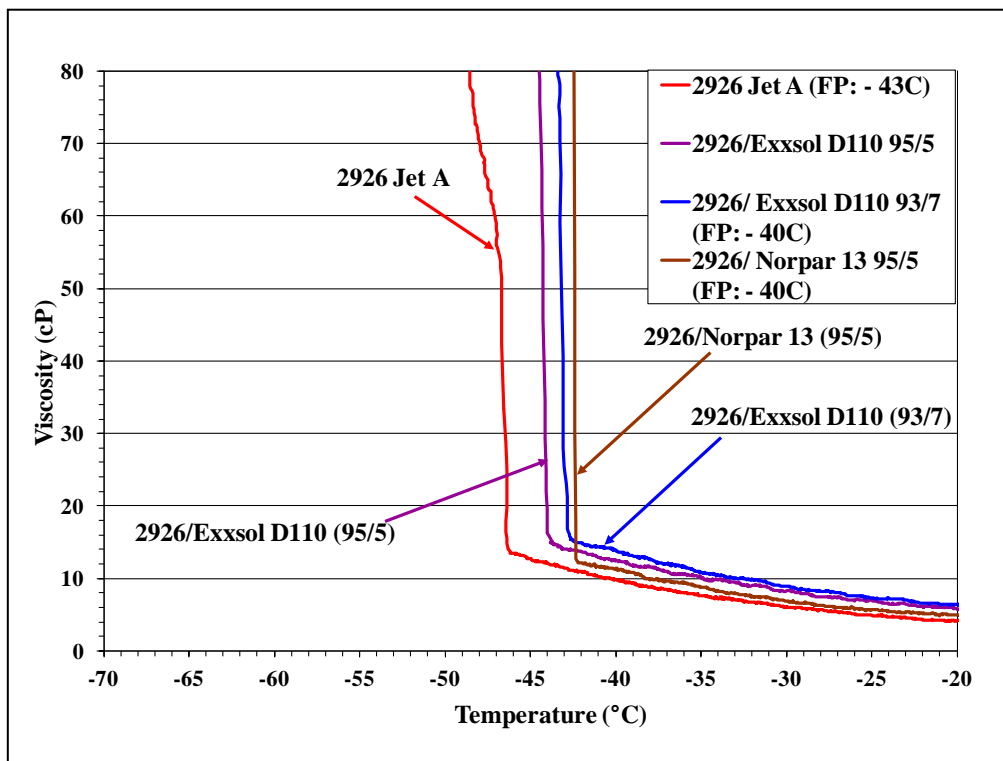


Figure 7. Plots of dynamic viscosity vs. temperature for a -40°C freeze point fuel blend with various amounts of LT additive

Figure 8 shows plots of dynamic viscosity obtained by the scanning Brookfield technique as a function of additive concentration. The figure shows that POSF-7463 exhibits a knee in the viscosity curve near -43°C , indicating the onset of fuel solidification. The figure also shows that 2000 to 6000 mg/L (active) of the additive inhibits this rapid solidification, producing a more gradual increase in viscosity with decreasing temperature. While the higher levels of additive improve the viscosity the greatest amount at the lowest temperatures (below -60°C), the 2000 mg/L level provides the lowest viscosity over the temperature range -43 to -57°C . For comparison, the figure also shows the viscosity of a JP-8 fuel. While the additive inhibits formation of the viscosity knee, the viscosity of the additized fuel blend is higher than the JP-8 fuel for temperatures greater than -52°C .

Scanning Brookfield measurements made to measure the effect of the additive on two Jet A fuels are shown in Figures 9 and 10. The results are very similar to the blend results shown above. For both POSF-2926 and POSF-3683, the highest additive concentrations work best at the lowest temperatures, but the 2000 mg/L (active) level works well over the important temperature range

-46 to -58 °C. Again, the Jet A with LT additive fuels display viscosities that are higher than the JP-8 fuel over the temperature range -35 to -52 °C.

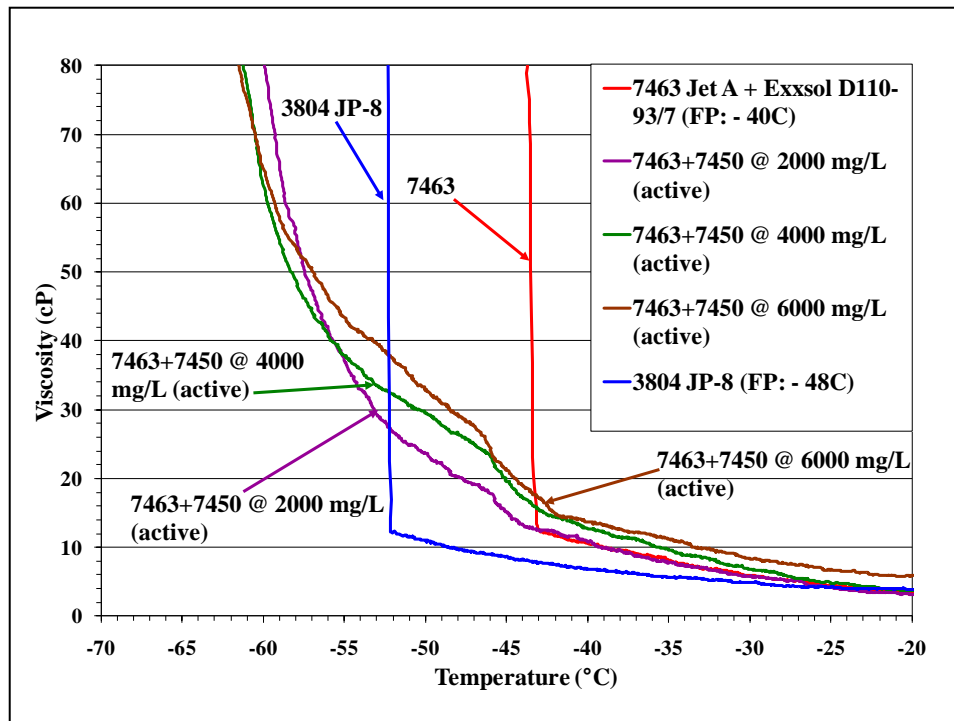


Figure 8. Plots of dynamic viscosity vs. temperature for a -40 °C freeze point fuel blend with various amounts of LT additive

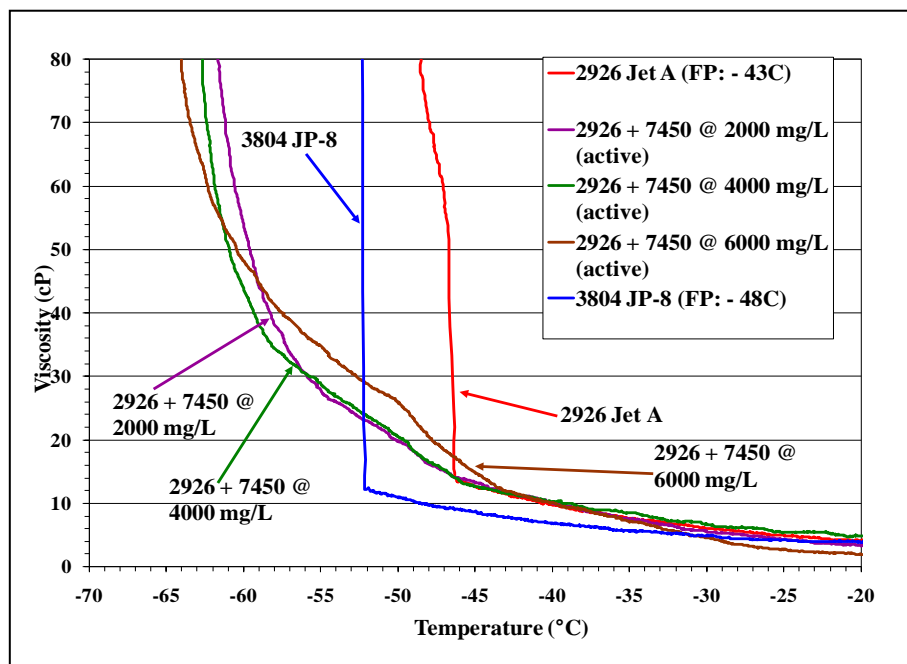


Figure 9. Plots of dynamic viscosity vs. temperature for Jet A fuel POSF-2926 with various amounts of LT additive

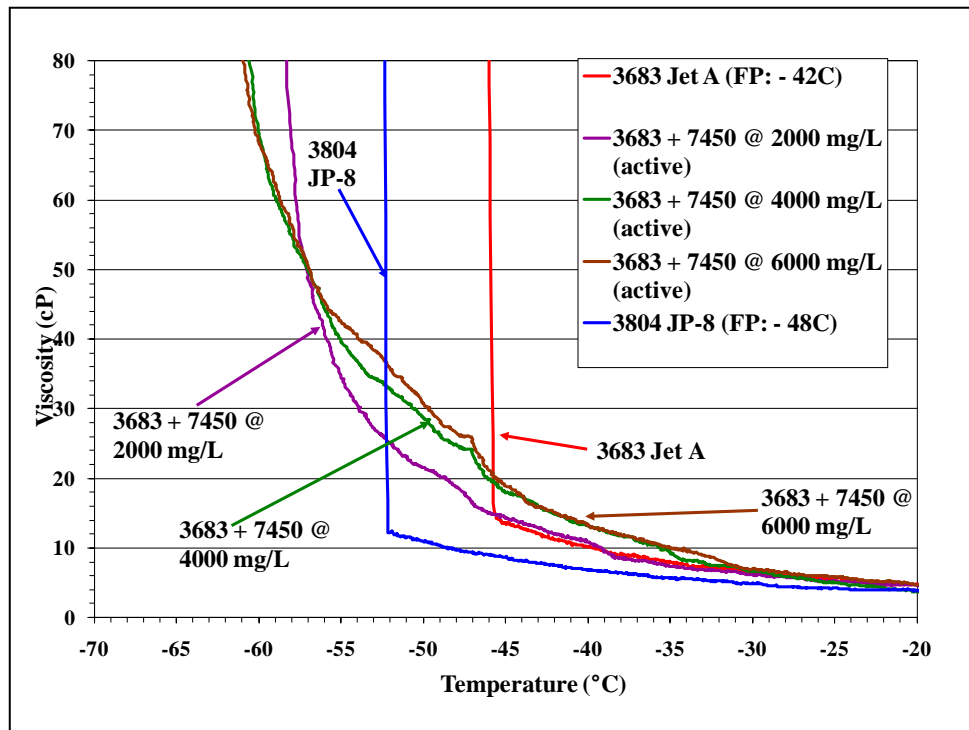


Figure 10. Plots of dynamic viscosity vs. temperature for Jet A fuel POSF-3683 with various amounts of LT additive

Experiments were also conducted to examine the performance of older samples of the LT additive versus new samples. These studies were performed to examine the efficacy of the additive after significant aging. The old additive (POSF-4955) was received in June 2006 and stored at ambient conditions in the laboratory, while the new additive was received in December 2010. The results are shown in Figure 11. The figure indicates that there is very little difference in performance between the old and the new additives. This shows that the additive performance does not degrade significantly during ambient storage.

Figures 8 to 11 show that the LT additive may increase the fuel viscosity at low temperatures above that of the unadditized fuel, especially when used at higher concentrations (>2000 mg/L active). The data also show that the additized Jet A fuels display higher viscosities than the JP-8 comparison fuel. One important concern is that the viscosity at low temperature is low enough to permit adequate fuel atomization for low temperature ignition for engine restart. In particular, in discussions with Randy Williams of Honeywell he has indicated that APU's have more severe restart conditions than propulsion engines. On many aircraft these APU engines can cold soak for up to 14 hours at high altitudes, with restart required under very low temperature conditions. Honeywell currently recommends a 12 cSt limit for Jet A fuels at -37 °C and a 12 cSt limit for Jet A-1/JP-8 fuels at -40 °C. At 15 cSt there is reduction in spray angle and spray droplet size that inhibits light off. In contrast to APU's, in propulsion engines there is usually a fuel/oil heat exchanger prior to the combustor which provides heat to the fuel before atomization. The amount of heat added is aircraft and flight condition dependent, so it is difficult to generalize the amount of heat that would be added via this heat exchanger.

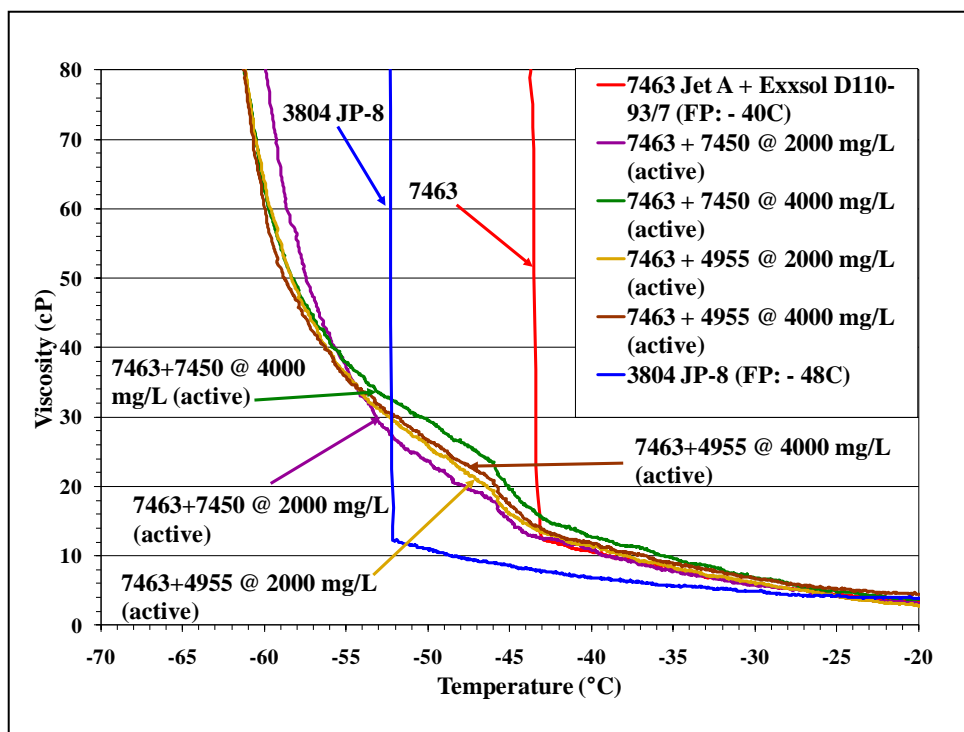


Figure 11. Plots of dynamic viscosity vs. temperature for the fuel blend with various amounts of old and new LT additive

In an effort to address this concern, the kinematic viscosities of three fuels with various levels of LT additive were measured via ASTM D445, and are shown in Table 3. The table shows that addition of the additive increases the fuel viscosity, but this increase is very fuel dependent. For example, fuel POSF-2926 shows an increase of 1.39 cSt upon addition of 6000 mg/L of the additive, while POSF-3683 increases by 3.81 cSt. Fuel POSF-2926 stays below 12 cSt upon addition of 4000 mg/L, while fuel POSF-3683, which has a higher starting viscosity, goes above 12 cSt even upon addition of only 1000 mg/L. The fuel/surrogate blend, POSF-7463 is above the 12 cSt value without addition of the additive, indicating that this blend may not be the best choice when evaluating the -40 °C viscosity behavior.

The differences between Honeywell’s viscosity limits for Jet A and Jet A-1/JP-8 fuels appear to consider that Jet A fuels will have higher viscosities at a given low temperature condition than JP-8 fuels, in agreement with our previous observations. To confirm these observations, we performed kinematic viscosity measurements on a number of Jet A, Jet A-1, and JP-8 fuels, neat and with the LT additive at 2000 mg/L (active) at -40°C. The results are shown in Table 4. The table shows that the eleven Jet A fuels display an average viscosity of 10.6 ± 1.5 cSt, while the eleven JP-8 fuels display an average viscosity of 9.4 ± 1.1 cSt. The data is also plotted in Figure 12, which indicates that there appears to be a relationship between measured freeze point and kinematic viscosity, with lower freeze point fuels displaying lower kinematic viscosities. The trend shown in the figure supports the observation that the average viscosity of the Jet A fuels is higher than that of the JP-8 fuels. The table also shows that five of the eleven Jet A fuels do not meet the 12 cSt limit when the LT additive is employed, and one of the fuels does not even meet the limit without the additive.

Table 3. Measured Kinematic Viscosity (cSt) via ASTM D445 at -40°C

Additive concentration	Fuel POSF Number		
	7463 (-40C FP)	2926 (-43C FP)	3683 (-42C FP)
Neat	12.41	10.88	11.95
1000	12.77	11.02	12.13
1500	12.87	11.14	12.47
2000	13.01	11.15	12.79
4000	15.00	11.50	15.47
6000	16.17	12.27	15.76

Table 4. Kinematic Viscosity (cSt) Measurements of Fuels at -40C

POSF	Type	FP (°C)	w/o LT additive	with LT additive
7463	Jet A	-40	12.4	13.0
3683	Jet A	-42	12.0	12.8
3688	Jet A	-42	10.7	11.2
2926	Jet A	-43	10.9	11.2
3686	Jet A	-43	12.2	13.2
3166	Jet A	-45	11.3	12.1
3084	Jet A	-46	10.8	11.8
3694	Jet A	-50	9.6	10.8
3638	Jet A	-53	7.8	8.3
3602	Jet A	-54	10.6	12.3
3633	Jet A	-56	7.4	8.0
Jet A Average			10.5	11.3

POSF	Type	FP (°C)	w/o LT additive	with LT additive
3219	JP-8	-47	10.7	11.6
3804	JP-8	-48	8.3	8.6
4336	JP-8	-48	13.7	14.8
4339	JP-8	-48	8.8	9.1
3773	JP-8	-50	8.1	8.2
4751	JP-8	-50	9.9	10.3
6169	JP-8	-50	8.7	9.3
4908	JP-8	-51	11.1	12.3
5699	JP-8	-51	8.0	8.5
4911	JP-8	-52	9.4	N/A
4177	JP-8	-56	10.2	11.1
JP-8 Average			9.7	10.4

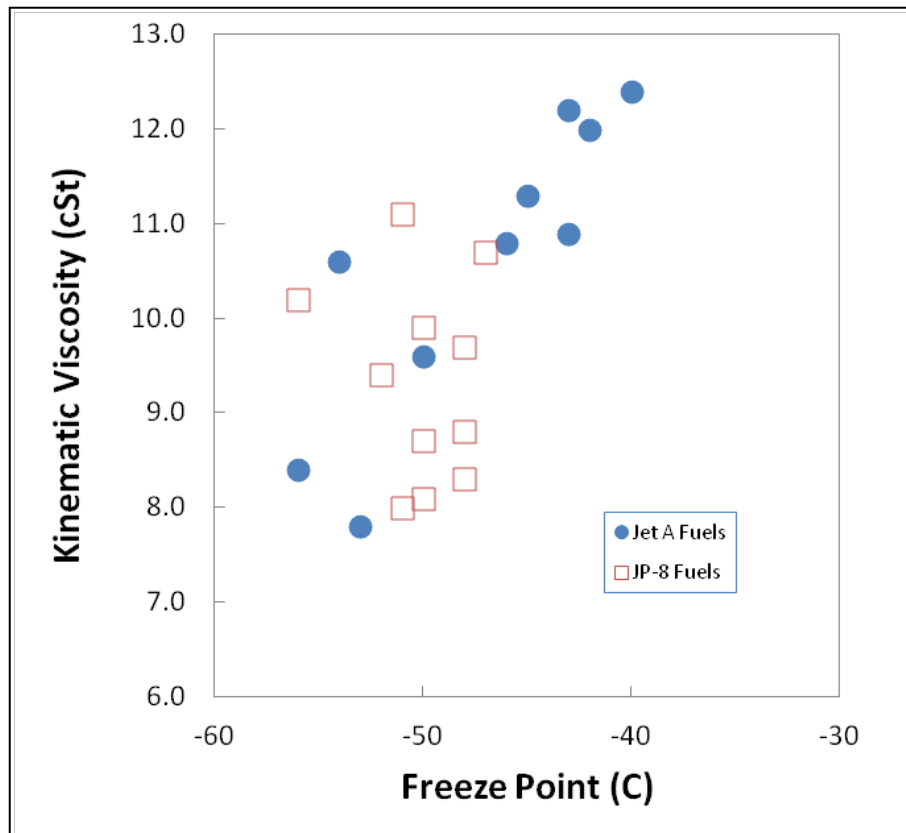


Figure 12. Plot of freeze point vs. kinematic viscosity for a range of Jet A and JP-8 fuels

The LT additive was developed and designed to improve the flowability of JP-8 fuels to that of JP-TS for use in one specific platform, the U-2 aircraft. In this aircraft, small increases in fuel viscosity caused by the additive were not of concern, as the fuel is gravity fed from the wing tanks to the body tank through relatively wide tubing. The primary concern for the U-2 was hold-up of fuel in the wing tanks and the additive was designed to allow JP-8 fuel to flow down to -53 °C conditions.

The intent of the use of Jet A fuel with the LT additive is for mission situations where the specification freeze point of Jet A fuel without the LT additive is not sufficient to guarantee proper fuel system operation. Unfortunately, the increase in viscosity beyond the -40 °C limit of 12 cSt observed upon addition of the additive to Jet A fuel, may limit the use of the additive in Jet A fuels. In addition, the determination of the suitability of the use of Jet A with the LT additive is likely highly aircraft and fuel system dependent. Thus it may not be prudent or possible to approve all aircraft for its use. For example, a fuel system which puts significant heat into the fuel via, for example, a fuel/oil heat exchanger prior to the combustor, may experience no problems due to the increased fuel viscosity caused by the additive. However, another fuel system that puts less heat into the fuel, such as for an APU turbine engine, may have significant issues. Unfortunately, these implications will have to be evaluated on an individual aircraft model basis.

3.4 APU Cold Start Issues

A teleconference was held June 28, 2011 with Mr. Randy Williams of Honeywell. This was attended by AFRL, UDRI, and AFPET workers. Honeywell manufactures many of the APU turbines that are used in commercial and military aircraft. Previous discussions with Randy and others have indicated that APU operations may be a worst-case scenario for employing Jet A fuel during high altitude, long duration military flights. In some aircraft, the APU is turned off during much of the flight and then needs to be restarted after cold soaking for long periods. This is exacerbated by the lack of fuel/oil heat exchangers prior to fuel control or fuel filters as are typically used in the fuel feed for the propulsion engines. As a result the APU is subjected to very low temperatures and may have to be restarted after long cold soak periods with no direct source of heat to warm the fuel. Some of the more important issues for low temperature APU operation are listed below:

1. According to Randy, one major concern is the APU fuel inlet filter. APU's either have a 40 μm fiber mesh inlet filter or a 20- μm wire mesh/screen at the atomizer. It is likely that fuel flow will be restricted if any wax crystals are directed towards these filters, particularly the fine 20 μm filter. It is unclear if the filters have bypass circuits which will bypass fuel around the filter if it becomes plugged. It is important to note that the LT additive is not designed to prevent crystal formation below the fuel cloud point, but rather the additive changes the crystal morphology preventing formation of a crystal matrix that inhibits fuel flow. Thus, below the fuel cloud point Jet A with the LT additive will contain needle-like crystals that may plug these APU fuel filters.
2. Honeywell APU's are designed to start and operate with fuel that is ≤ 12 cSt. The data reported previously showed that while even JP-8 fuels sometimes exceed this value at -40°C , Jet A fuels and Jet A fuels with the LT additive exceed this value significantly more frequently.
3. On some aircraft there are opportunities for fuel to be heated before reaching the APU fuel filter. These include fuel passage through heated compartments and the presence of other heating sources, such as warm bays in the F15 aircraft. This heating can ameliorate some of these issues
4. Randy was not able to confirm that APU's are run continuously in military aircraft. APU's are not run continuously in commercial aircraft and thus high altitude relight is required. The continuous operation of the APU in military aircraft is an unanswered question that needs to be considered further. The system program offices may be good sources for this information.
5. The C-130 aircraft has the same APU as the older Boeing 737. Unfortunately, this APU is known for problems with low temperature starting. Some of these aircraft were upgraded with electronic controls which may help with this issue. These C-130 aircraft APU may be a worst-case aircraft for use of Jet A fuel with the LT additive.
6. For APU/aircraft interface design Jet A fuels are limited to a temperature of -37°C for cold start, while JP-8/Jet A-1 fuels are limited to a temperature of -40°C . Operation with Jet A with the LT additive would subject the fuel to the JP-8 operation limits.
7. APU cold start issues were observed during the JP-4 to JP-8 conversion.

8. Some fighter aircraft, such as the F-15, have a rapid start requirement which can be more challenging for the APU, although fighter aircraft may not see the low temperatures and long duration flights that transport and bomber aircraft encounter.

3.5 Small-Scale Icing Simulator and Crystallization Visualization Studies

3.5.1 Evaluation of Fuel Flow and Filter Plugging Characteristics with LT Additive

The LT additive has been shown to function by suppressing a rapid rise in fuel viscosity and large crystal formation as the fuel temperature is reduced below the specification freeze point. However, the fuel viscosity will continue to increase as the temperature is reduced, approaching values which can be significantly higher than during operation with typical JP-8 fuels. Despite the formation of solids and increasing viscosity, suppressing the rapid viscosity rise was found to be adequate for operation of the U-2 and Global Hawk platforms since these fuel systems do not have fine flow restrictions (e.g., fuel filters or screens) prior to fuel heating. However, fuel systems designs and associated conditions (e.g., temperature) vary substantially, and may include the presence of fuel filters and screens where solids can accumulate and impede fuel flow or high viscosity results in high differential pressures. Performance evaluation for the LT additive in Jet A is not standardized and strategies for evaluation are typically developed on a system or component-specific basis. However, evaluation of the effect of the LT additive at a reduced-scale as a function of the pertinent variables in a flowing system, which include temperature, fuel flow rate, screen type and flow passage size can provide insight into the potential applicability for implementation. For the purposes of this program, the primary temperature range of interest is from -40 to -47 °C, which encompasses the difference between the specification freeze points for Jet A and JP-8, respectively.

Evaluation of the effect of the LT additive on flow characteristics and filter plugging was performed using a recirculating fuel system, which allows a 'system-independent' basis for comparison. An experimental system, termed the Small-Scale Icing Simulator (SSIS), was used during this testing to provide data regarding the effect of additive concentration and fuel temperature on the flowability of the fuel. The SSIS was developed and used in a previous research program to evaluate the effectiveness of Fuel System Icing Inhibitor (FSII) additives to prevent formation of ice and blockage of fuel filters and screens (DeWitt et al., 2010). A flow diagram of the SSIS system is shown in Figure 13. During testing, fuel is recirculated through the fuel system at a constant flow rate and passed through a test article (typically a filter). The flowability of the fuel is determined via measurement of the fuel pressure at the outlet of the pump (termed system pressure), across the test article (termed differential pressure), and the required pump speed to maintain the fuel flow rate. The system pressure provides guidance regarding the viscosity and flowability characteristics of the fuel while the differential pressure provides guidance related to blockage of fine tolerance passages or the effect of high viscosity fluid flow. The fuel temperature is reduced incrementally using a counter-current heat exchanger and environmental chamber and steady-state flow data is collected until a significant decrease in flowability occurs. Reproducibility is performed by warming of the fuel to greater than -35°C and repeating the test methodology. Once completed, the LT additive is added to the initial target concentration and testing performed. The concentration is then incrementally increased to obtain data over the concentration range of interest.

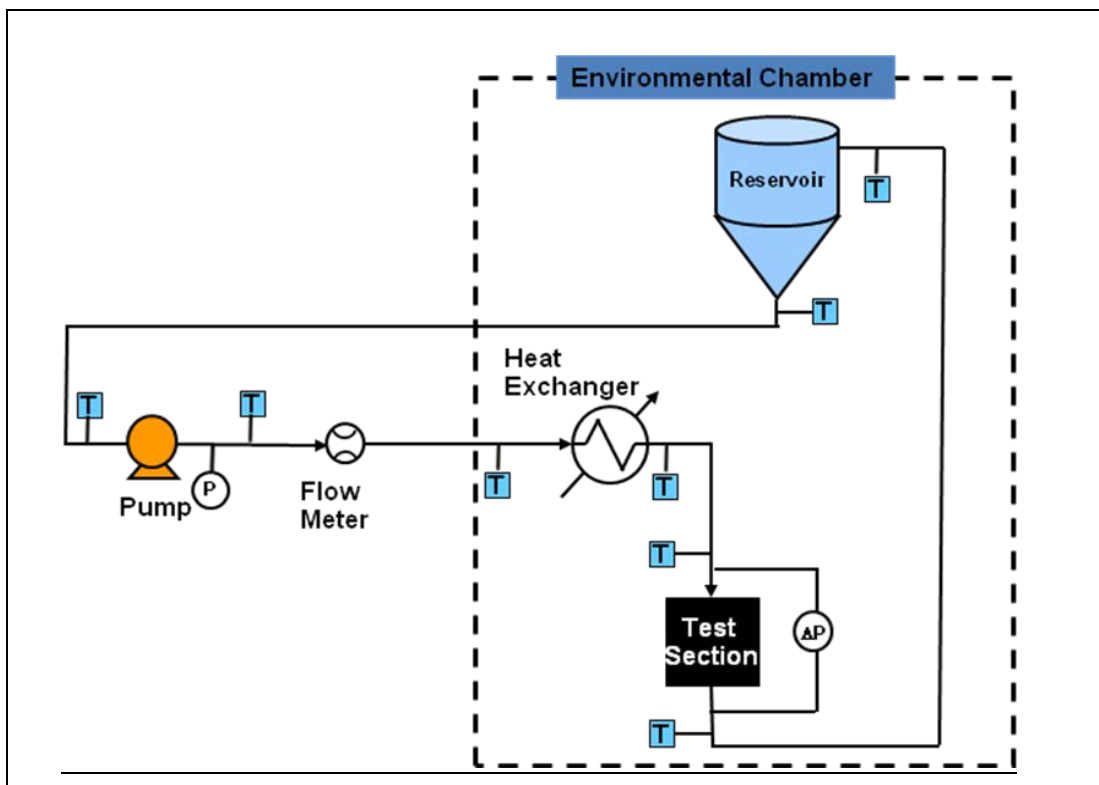


Figure 13. Flow schematic of the Small-Scale Icing Simulator

3.5.2 Flow Testing with B-52 Fuel Strainer Element

Studies were initiated by performing recirculating flow testing with a Jet A fuel (POSF-2926) with 0.10% DiEGME. The flow system was operated at a constant flow of 500 mL/min using a 1-inch diameter circular cross section of the cellulose filter used in the fuel strainer of the B-52 (nominal openings of $\sim 25 \mu\text{m}$) in a conical filter holder as the test article. The B-52 strainer was chosen for evaluation as it is potentially prone to blockage due to face plugging, is the first fine flow passage in the B-52 after the fuel is transferred from the fuel tanks, and is not actively heated. During testing, the fuel temperature was reduced incrementally until a significant decrease in flowability was observed. This is determined by a decrease in the measured flow rate/minimum require pump speed and increase in system and differential pressures. Results from repeatability testing with the neat Jet A are shown in Figure 14. The pre-filter temperature corresponds to the location immediately upstream of the test article. As shown, there was good reproducibility in the measured pre-filter temperature ($\sim -44^\circ\text{C}$) at which both the system and differential pressures increase. This temperature is below the specification freeze point and slightly above the ‘knee’ of the scanning viscosity curve. To achieve a pre-filter temperature of -44°C , the heat exchanger required approximately a 2 to 3 $^\circ\text{C}$ lower inlet coolant temperature. The concurrent increase in both the system and differential pressures are indicative of a bulk transition to higher viscosity of the fuel. These results, in combination with the viscometer data, indicate that the unadditized fuel will not be readily flowable below the measured failure temperature.

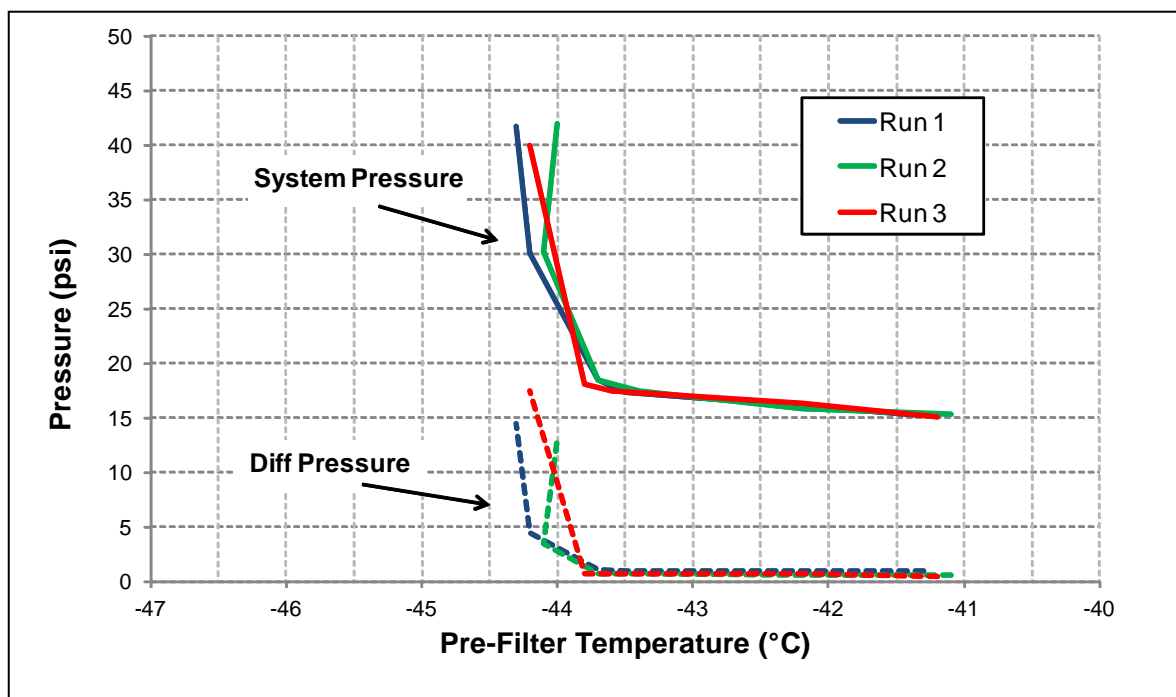


Figure 14. System and differential pressures as a function of fuel temperature for repeatability testing with Jet A fuel (POSF-2926)

The effect of the LT additive on flowability and filter blockage was investigated by performing recirculating studies while varying the concentration of additive in the fuel from 500 to 4,000 mg/L. Results from this testing, along with the neat Jet A results, are shown in Figure 15. The data are averages of multiple (2 to 3) tests performed at each condition. Addition of the LT additive significantly improved the flowability compared to neat Jet A, with the increase in the system pressure observed at lower temperatures, which is consistent with scanning viscometry results. For example, addition of 2,000 mg/L LT additive allowed flowability to the JP-8 fuel specification freeze point. However, the fuel viscosity was increasing, as indicated by the higher system pressure and slight increase required in pump speed. It was difficult to deconvolute a decrease in flowability due to viscosity increase compared to potential filter plugging due to fuel crystals in the current testing, but the lack of a significant rise in the differential pressure suggests the increasing viscosity (primarily in the heat exchanger) is the dominant cause for reduced flowability. Increasing the additive concentration to 4,000 mg/L appeared to have a detrimental effect on flowability, as failure was observed at a higher temperature. Overall, the LT additive does improve the flowability compared to neat Jet A, but the increase in viscosity may be a potential issue for both transfer/flow and obtaining adequate fuel atomization and spray characteristics in the combustor.

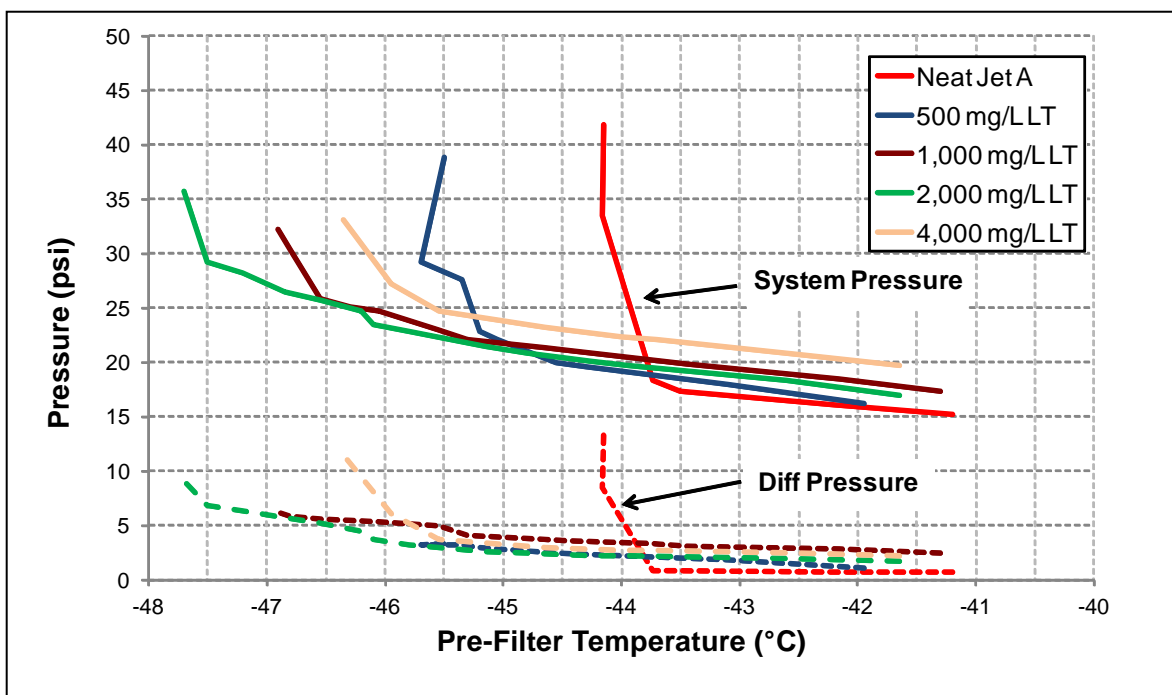


Figure 15. System and differential pressures as a function of fuel temperature and LT additive concentration in Jet A fuel (POSF-2926)

The behavior of the LT additive in JP-8 fuel (or Jet A-1) had been previously considered in the JP-8+100 LT program, but limited evaluation of the LT additive performance in Jet A-1 was performed in this program to determine if the basic function of the LT additive is similar in the different types of fuels. Testing was performed with a Jet A-1 (POSF-4877; FP = -52°C, viscosity knee ~ -54°C), both neat and 1,000 mg/L of the LT additive. Results from this evaluation compared to the Jet A testing are shown in Figure 16. With addition of the LT additive at 2,000 mg/L, the flowability temperature was reduced from approximately -52 to -54°C, with identical behavior to that for the Jet A testing. The general effect of the LT additive is similar in both fuel types, suppressing the temperature at which a significant reduction in flowability is encountered. These results imply that for aviation fuels of interest, the LT additive will most likely function in a similar manner over the applicable temperature range (from -40 to -47°C). This data is consistent with scanning viscosity studies previously performed. It should be reiterated that an equivalent temperature, the viscosity for a Jet A fuel will typically be higher than for a Jet A-1/JP-8. Therefore, even though the LT additive may inhibit the rapid rise in bulk viscosity, there will continue to be an increase in the viscosity which will increase the resistance to flow and require higher pumping capabilities for equivalent mass flow.

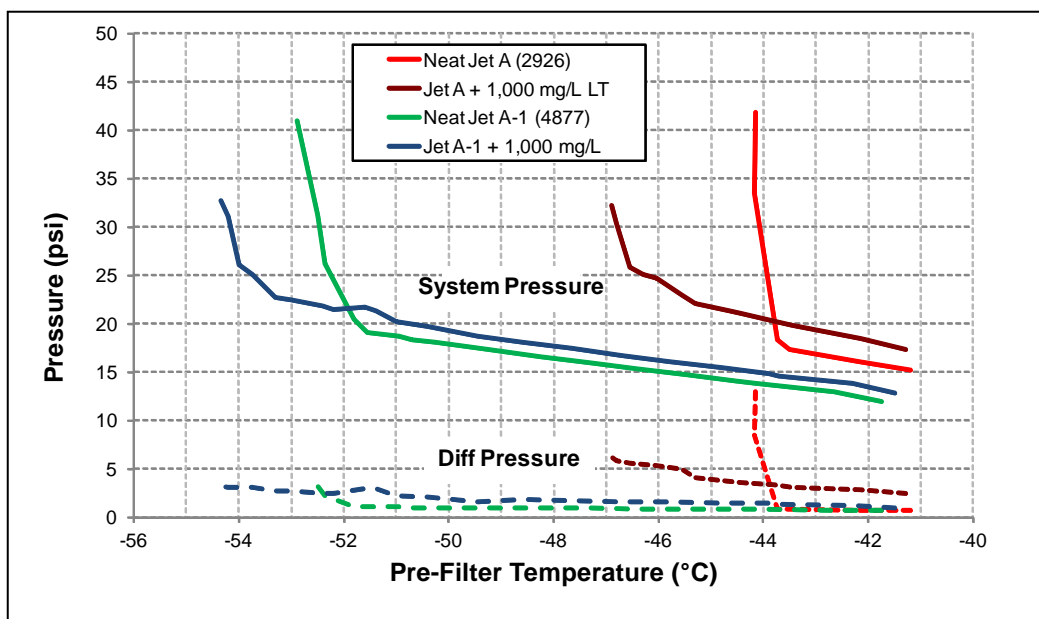


Figure 16. System and differential pressures as a function of fuel temperature and LT additive concentration in Jet A and Jet A-1 fuels

3.5.3 Flow Visualization Testing

Based on the results from the recirculating flow testing, visualization studies were performed to attempt to provide guidance regarding the primary mechanism for the decrease in fuel flowability. Therefore, the filter holder in the SSIS was replaced with an optical cell which allows visual access to the flow field and filter section during testing. Photographs of the optical cell are shown in Figures 17 (a) and (b). The optical cell is square and was implemented in the system with downward flow. A 1- by 1-inch-square cross section of the B-52 cellulose filter was installed between the upper and lower cells, allowing for visualization of the fuel both pre- and post-filtration. The upper cell had a thermocouple installed to obtain an accurate measurement of the fuel temperature near the filter interface.

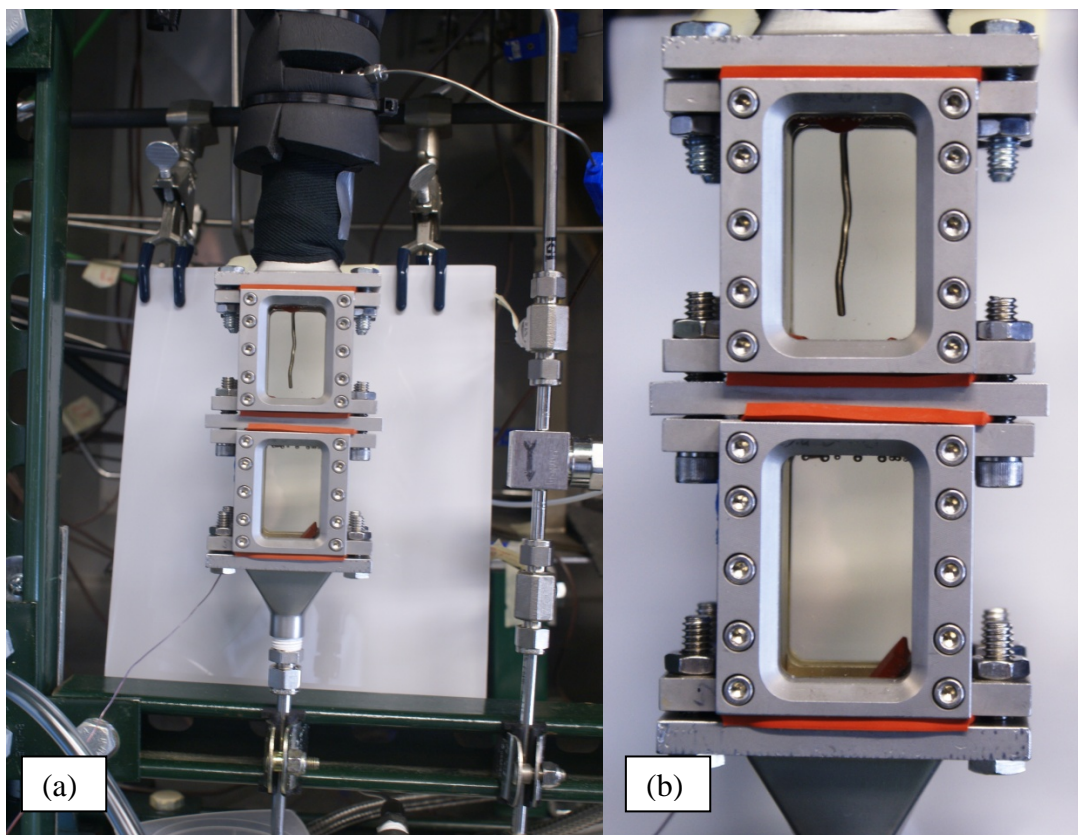


Figure 17. Photographs of optical cell installed in the Small-Scale Icing Simulator

Studies were performed with neat Jet A fuel and with 2,000 mg/L of the LT additive. The neat Jet A testing showed similar flow behavior to that observed for the preceding studies, where the system and differential pressures increased as the pre-filter temperature approached $-44\text{ }^{\circ}\text{C}$. During the cooling portion of the testing, visible crystals were not observed in the optical cell/filter interface. This result implies that the reduction in flowability is most likely dominated by the rapid increase in the bulk viscosity of the fuel, rather than face plugging. Flow visualization testing with 2,000 mg/L of the LT additive was also generally consistent with the preceding studies, but a higher increase was observed in the differential pressure measurement. The system and differential pressures gradual increased during the step-wise fuel cooling, with a concurrent increase in the required pump speed to maintain fuel flow. A gradual reduction in fuel flow through the optical cell occurred as the temperature was reduced. In addition, an increase in fuel density (as inferred via light transmittance) also occurred. Transition to channeling of flow through the optical cell could be observed, with portions of the flow field being stagnant. Once the temperature limit was reached, fuel flow was not readily observed through the optical cell. Therefore, it appeared that the primary resistance to flow was the bulk fuel viscosity rather than filter face plugging. Upon warming of the heat exchanger, an interesting phenomenon was observed. Fuel flow through the optical cell gradually increased, until a rapid rise in flow occurred with release of large amounts of visible fuel crystals. Images obtained during the various steps described are shown in Figure 18. It appeared that the crystals did not pass through the filter element, indicating that the potential exists for the crystals to accumulate at fine flow restrictions. However, the overall accumulation in the test was

insufficient to completely block the fuel filter. It is hypothesized that the LT additive/crystals were selectively forming/accumulating on the internal surfaces of the heat exchanger, since this cooling surface was the coldest temperature in the system. The crystals were released upon warming of the heat exchanger and transferred into the optical cell. It was concluded that to be able to evaluate the potential for blockage of fuel filters by crystals in a flowing environment, a larger-scale system and different cooling strategy would be required. More specifically, a cooling methodology which maintained the LT additive/fuel crystals in suspension is required, which would then allow the fuel/solid mixture to be transferred to a filter interface for evaluation of potential blockage. It was determined that this type of evaluation was outside the scope of the current efforts, and insight into the potential for crystal formation and filter blockage would be inferred by using systems which employed static cool-down of the test fuel.

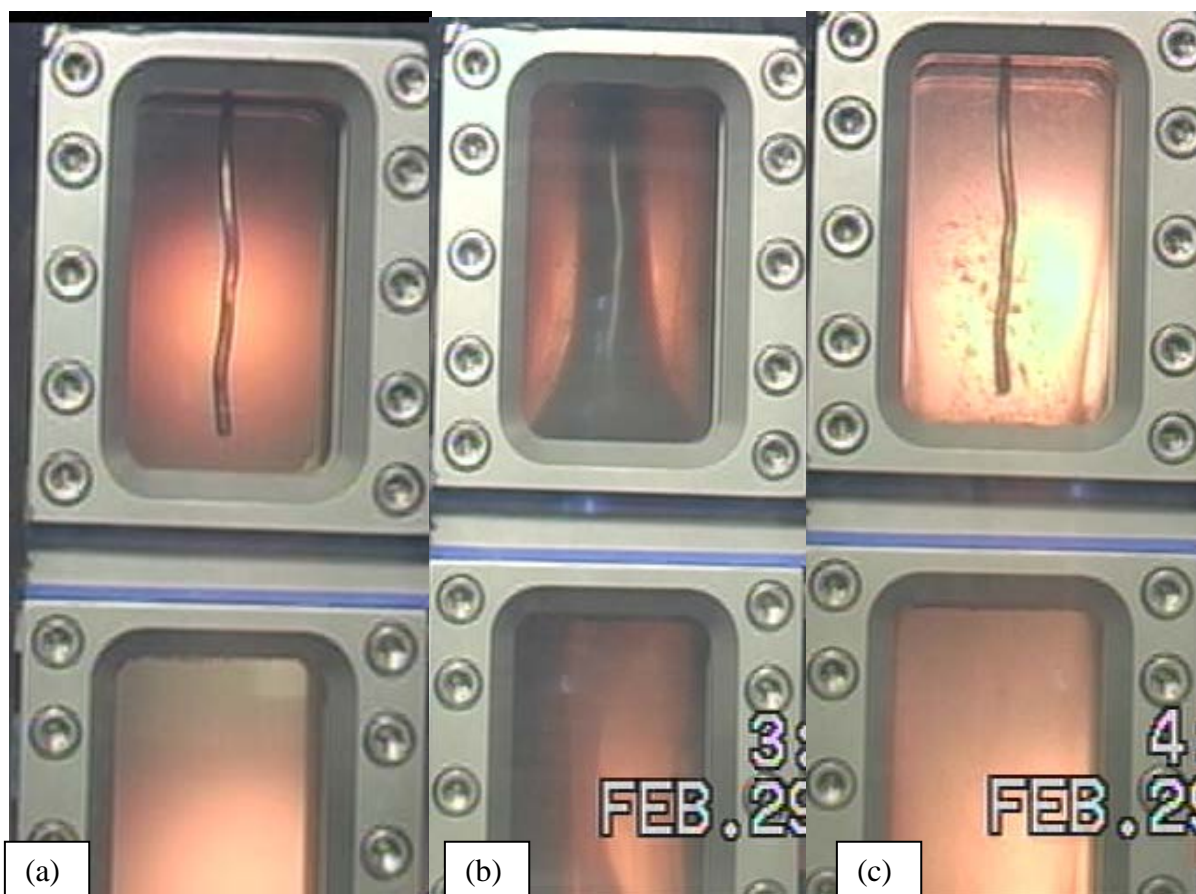


Figure 18. Photographs of optical cell during testing of Jet A-1 (POSF-2926) with 2,000 mg/L LT additive. (a) Image during cool-down of fuel with flow. (b) Stratification of flow as viscosity increases with reducing temperature. (c) Increase of flow and release of fuel/LT additive crystals upon warming of heat exchanger

3.5.4 Static Visualization Testing with LT Additive

Static visualization studies were performed to provide guidance regarding the effect of the LT additive on the nature of solidification and crystal formation/morphology within jet fuels. This information assists with flow visualization studies and understanding if fuel crystals can impede fuel flow across close tolerance pathways. Visualization was performed using neat Jet A (POSF-

2926), neat Jet A-1 (POSF-4877), a 50/50% blend by volume of the fuels, and 1,000 mg/L of the LT additive in each fuel. Kinematic viscosity curves for these fuels are shown in Figure 19. As previously discussed, the LT additive suppresses the temperature for the rapid rise (i.e., knee) in viscosity, which will most likely allow enhanced flowability at reduced temperatures.

The visualization studies were performed by adding 50 mL of fuel into 60 mL polycarbonate containers, sealing the container and placing a thermocouple into each fluid. The containers were placed into an environmental chamber and steady-state temperature was varied from -46 to -56°C, which encompasses the range of interest for these samples. Photographs were taken at each condition and qualitative interpretation was performed. Photographs of the test samples over the temperature range studied are shown in Figures 20 to 22. Slight differences in the brightness between some of the pictures (e.g., Jet A-1 at -46 and -48 °C) are due to the image capture/lighting technique. The neat jet fuels showed a high degree of structured crystallization and solidification at temperatures near the viscosity knee (and cloud point). The translucent nature of the fuels indicates a high structure order of large crystals with the fuels. The fuel blend showed intermediate behavior to the neat fuels, with possibly a slight change in the bulk crystal morphology. Addition of the LT additive to each fuel resulted in a suppression in the temperature at which fuel crystallization was visually detectable, the size of the crystals and the homogeneity of the static fuel.

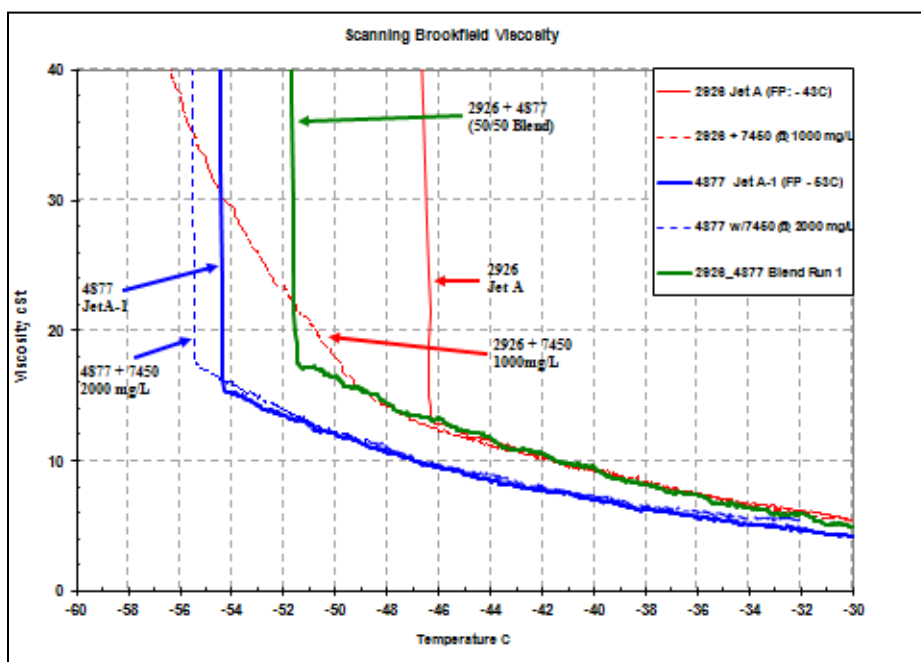


Figure 19. Kinematic viscosity curves for Jet A (POSF-2926), Jet A-1 (POSF-4877), a 50/50% blend by volume, and the neat fuels with 1,000 mg/L LT additive as a function of fuel temperature

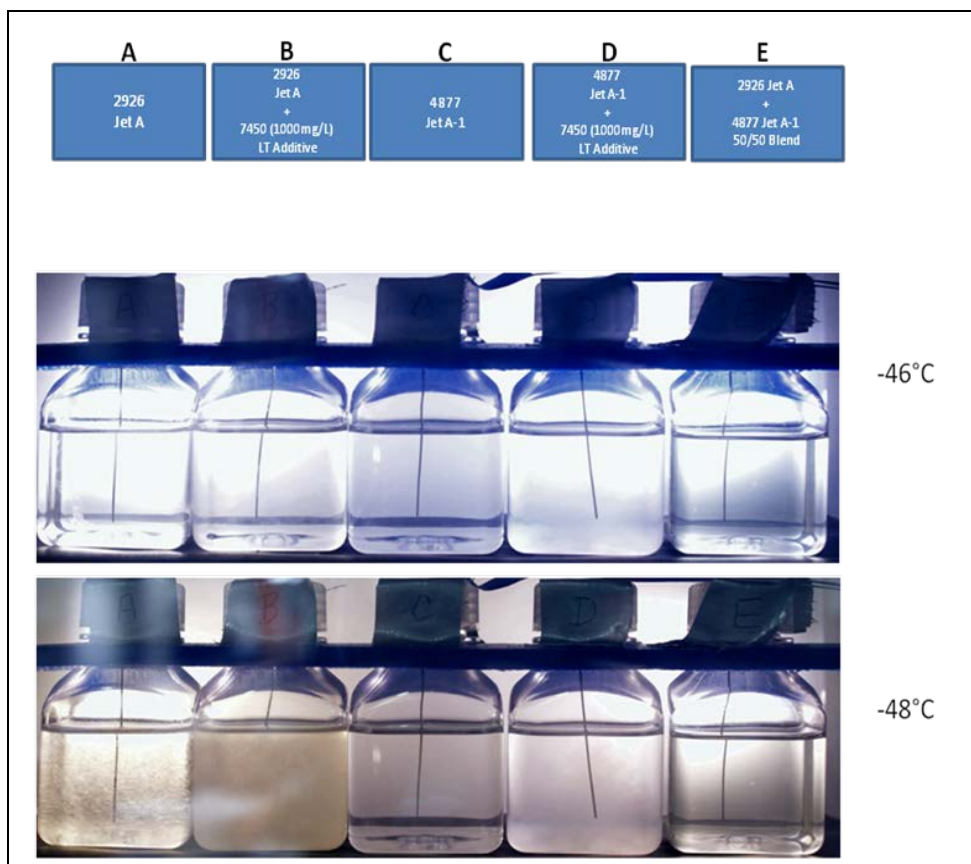


Figure 20. Static visualization of solidification of neat Jet A
Jet A-1 (POSF-4877), a 50% mixture by volume, and the neat fuels with 1,000 mg/L LT additive as at -46 and -48 °C

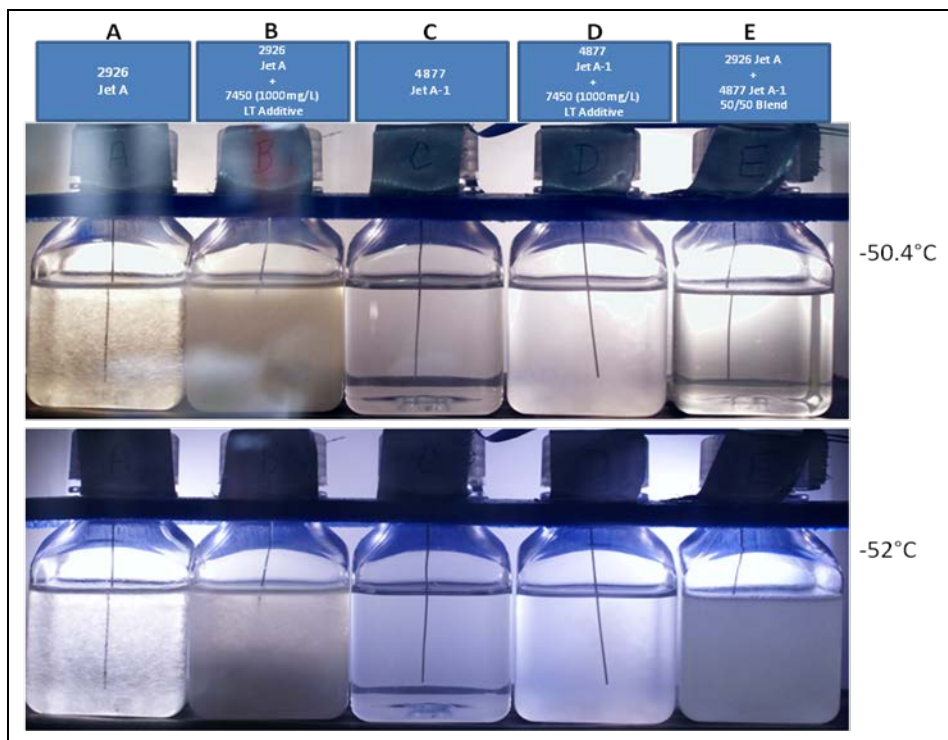


Figure 21. Static visualization of solidification of neat Jet A
Jet A-1 (POSF-4877), a 50% mixture by volume, and the neat fuels with 1,000 mg/L LT additive as at -50 and -52 °C

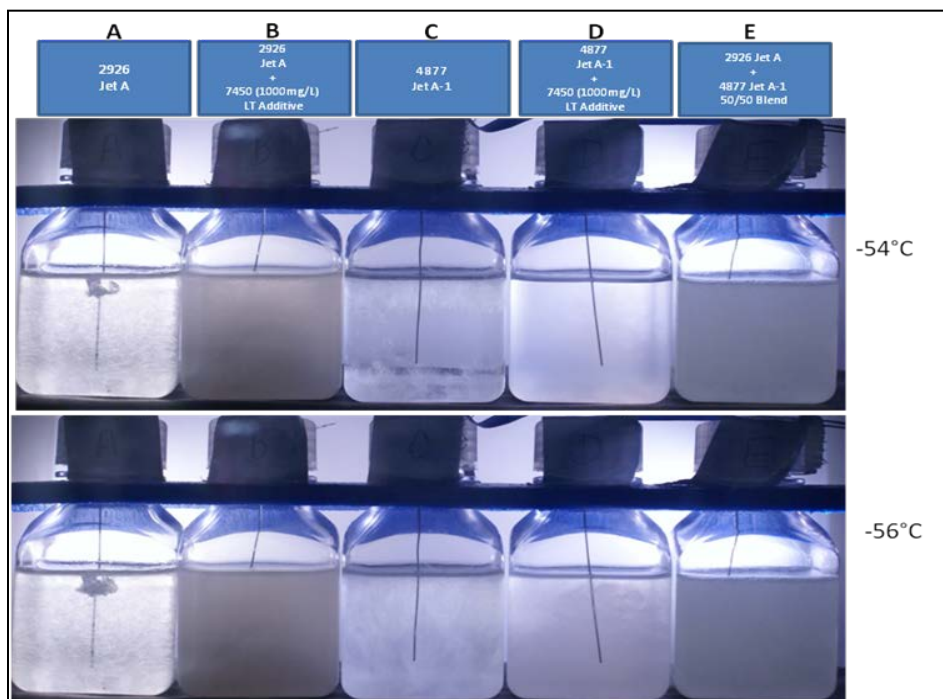


Figure 22. Static visualization of solidification of neat Jet A
Jet A-1 (POSF-4877), a 50% mixture by volume, and the neat fuels with 1,000 mg/L LT additive as at -54 and -56 °C

3.5.5 Static Cooling with Gravity Flow Testing

The flow testing with the SSIS verified that addition of the LT additive to Jet A (or Jet A-1) improves the flowability to temperatures below the specification freeze of the fuel. The additive prevents the rapid increase in the bulk fuel viscosity and inhibits large crystal growth in the fuel during cooling. The SSIS testing did demonstrate that the crystals formed with the LT additive can potentially collect on fuel filters, but it was not possible to determine if this can subsequently impede the overall fuel flow. As previously discussed, a different cooling and testing methodology would be required to specifically evaluate if the LT additive could completely block a flow filter/screen and prevent transfer of fuel flow. However, an experimental apparatus was designed and fabricated in this program to provide preliminary guidance regarding the effect of the LT additive on flow through a fuel filter under a gravity drain condition. This provides guidance regarding the effect of the LT additive on the bulk fuel viscosity and the potential for crystals to impede flow across the fuel filter. A schematic of the test apparatus is shown in Figure 23. The apparatus is comprised of an upper cell for conditioning of the fuel, a transfer line with shutoff valve, and a lower collection vessel. The apparatus is placed in an environmental chamber for isothermal conditioning; two units are tested simultaneously for direct comparison of the effect of the LT additive. The upper cell has square dimensions of 9.53 cm, height of 16.5 cm, and 0.32-cm-thick quartz walls, allowing for fuel volumes greater than 1.0 L for testing. The quartz walls allow optical access to the fuel during static cooling and subsequent flow evaluation. A cross-section of this cell is shown in Figure 24. The cell is outfitted with a thermocouple to measure the fuel temperature during conditioning and an upper vent port. The bottom of the cell tapers at a 23° angle to a 1.3-cm OD transfer line. A 1.9-cm circular filter is placed above the transfer line to filter the flow during flow. Once the desired test condition has been achieved, the flow valves are actuated using connecting levers which allow opening of the flow path from outside the environmental chamber. The test fuel then gravity drains to the collection vessel, which also has a vent port. The rate and total volume of fuel transferred is indicative of the flowability characteristics of the fuel. Visual access allows improved insight into whether fuel crystals impede fuel flow through the test filter.

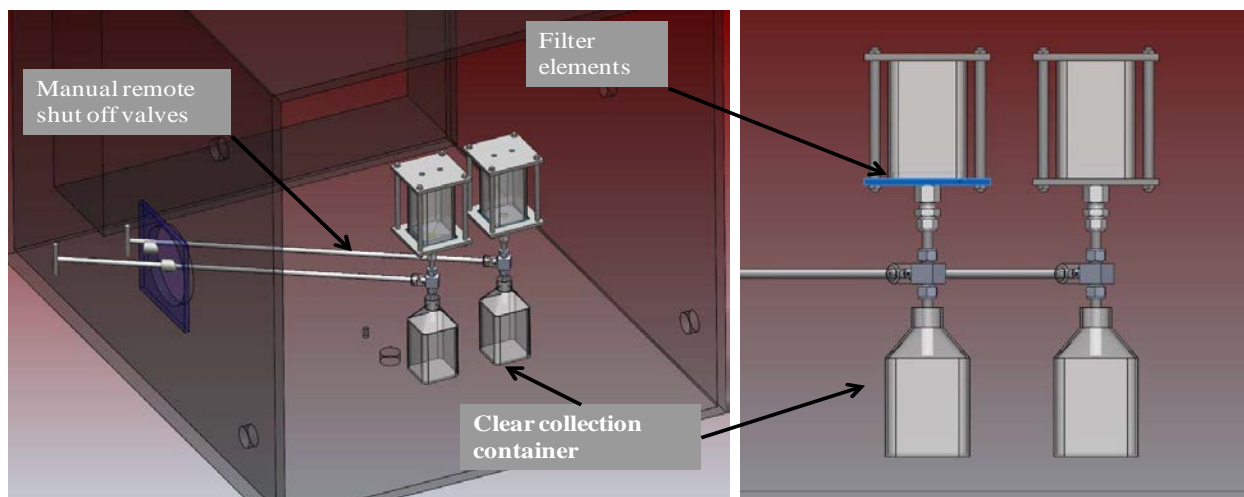


Figure 23. Image of test apparatus used for static condition and gravity flow evaluation of LT additive

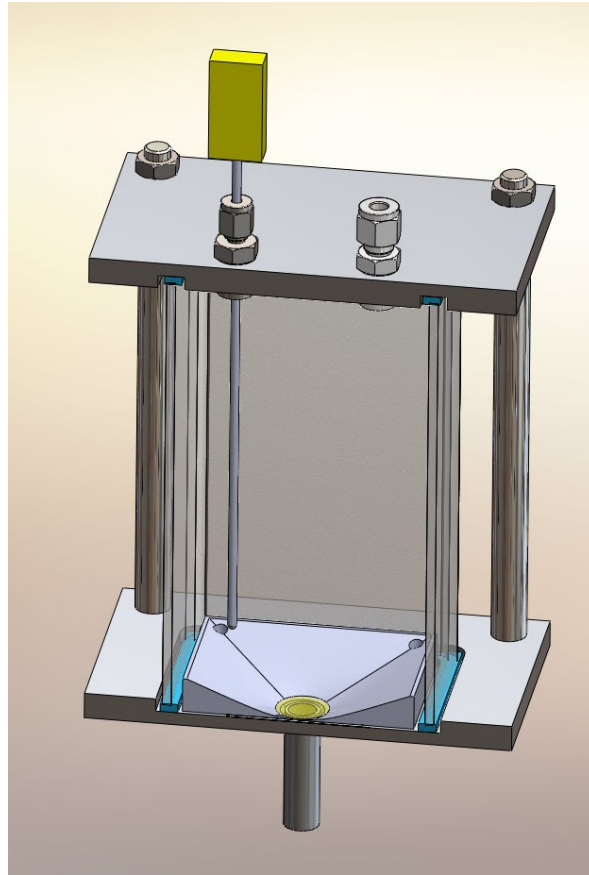


Figure 24. Cross section of conditioning cell used for static cooling and gravity flow evaluation of LT additive

Testing was performed with two gravity flow cells operated simultaneously. Each unit was identical, with a cross section of a B-52 fuel strainer element (nominal openings of $\sim 25\ \mu\text{m}$) placed above the drain line. The optical cells were placed into an environmental chamber and each filled with 1.0 L of test fuel; one was filled with neat Jet A (POSF-2926) while the second was filled with Jet A with 2,000 mg/L of the LT additive. Static cooling the test fuels was performed by incrementally decreasing the temperature of the environmental chamber from -44 to $-50\ ^\circ\text{C}$. Once the measured fuel temperature in the test fluids reached approximately $47\ ^\circ\text{C}$, the flow valves were opened allowing transfer to the collection vessels. Upon opening of the flow valve, differences were observed between the flow rates to the collection vessel. The neat fuel had a very low flow rate, which was in the form of slow drips. However, the LT additive cell initially had a continuous flow, subsequently slowing to the form of drips. After approximately 13 minutes of transfer time, fuel volumes of 25 mL (neat Jet A) and 90 mL (additized fuel) were collected. An image of the test vessels at the completion of the test duration is shown in Figure 25, the darker color of the additized fuel is an artifact of the lighting scheme used within the environmental chamber.



Figure 25. Photograph of test vessels upon completion of static condition and gravity flow testing of neat Jet A
(Left side) and Jet A with 2,000 mg/L LT additive (right side)

The ability of the LT additive to allow a larger volume of fuel to transfer is related to the reduced bulk viscosity relative to the neat fuel and the type of crystal formation within the fuels. The lower viscosity results in a reduced pressure drop, and hence, a higher extent of flow through the B-52 fuel filter. It should be reiterated that this test was performed with a gravity drain; an increase in head pressure would result in a higher flow rate through the fuel restriction. Crystals were readily observable in both the neat and additized fuel during the test. For the additized fuel, the crystals were near-uniformly suspended in the fuel. However, upon actuation of the fuel

flow, fuel crystals settled to the lower portion of the upper cell. An image of the upper cell at the completion of the test duration is shown in Figure 26. The relative locations of the fuel crystals are labeled since it is difficult to discern specific locations in the images. The additized fuel appeared to have a greater extent of packing at the bottom of the conditioning cell, which was most likely due to a large volume of fuel transfer resulting in compaction of the crystals. This was the most likely cause for the reduction in the fuel transfer rate for the additized fuel, and demonstrated that collection of fuel crystals formed by addition of the LT additive may inhibit flow through fine flow restrictions. However, additional studies under more applicable flow conditions are required to provide improved insight and quantitative data for application.

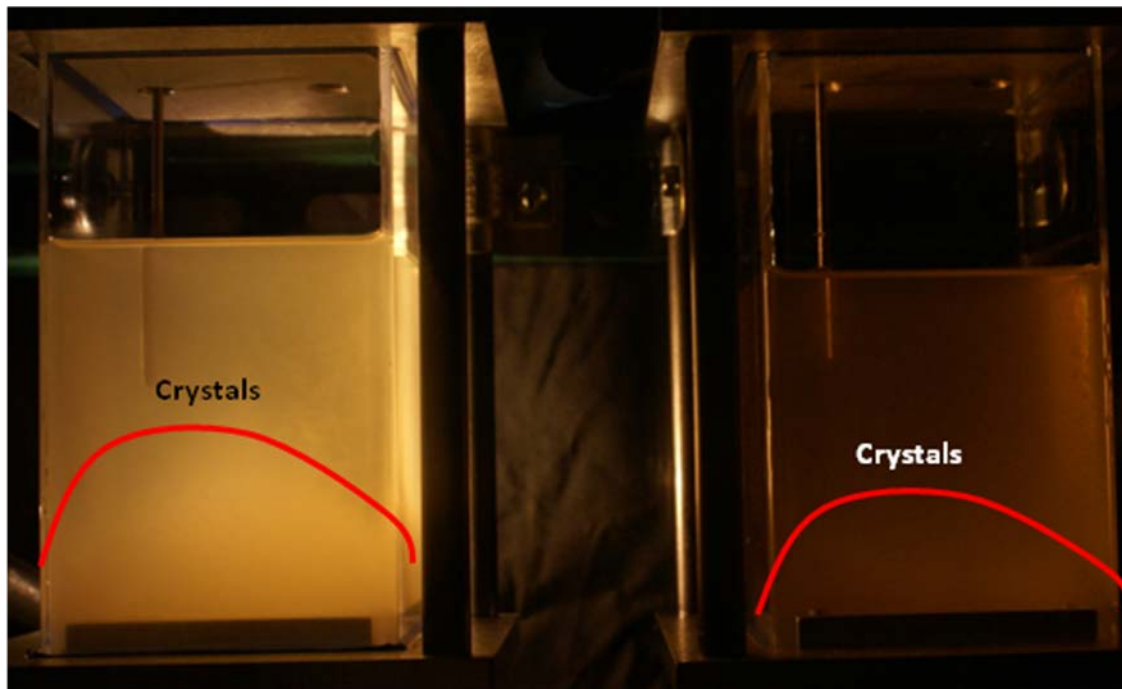


Figure 26. Photograph of conditioning cell upon completion of static condition and gravity flow testing of neat Jet A
(Left side) and Jet A with 2,000 mg/L LT additive (right side). Height of visible crystals in the bottom of the cells is labeled. Darker color of right image is due to lighting methodology employed

3.5.6 Solid Crystal Formation during Scanning Viscometry Measurements

Scanning viscometry measurements have shown that the LT additive inhibits the rapid rise in the viscosity of the neat fuel as the cloud point temperature is approached. Rather, the viscosity of the additized fuel continues to gradually increase at a consistent rate as the temperature is further reduced. The LT additive functions by selectively interacting with the specific compound classes in the fuel (e.g., long chain *n*-alkanes) which are known to increase the bulk viscosity and nucleate fuel solidification as the temperature is reduced. However, the LT additive does produce solid crystals which can be suspended or settle in the fuel.

An interesting observation was made during the scanning viscometry studies with the LT additive. The LT additive clearly prevented the viscosity transition of the bulk fuel. However, following nucleation and growth, the crystals settled to the bottom of the stator vessel. This behavior is shown for testing with neat Jet A (POSF-2926) and Jet A with 2,000 mg/L LT

additive at a test temperature of $-48.6\text{ }^{\circ}\text{C}$ in Figure 27. This temperature is below the viscosity knee of the neat fuel, which results in a high viscosity of the neat fuel ($\sim 56.5\text{ cSt}$) compared to the additized fuel ($\sim 18.8\text{ cSt}$). It can be clearly observed the neat fuel is homogeneously dense/cloudy throughout the stator, indicating the fuel is undergoing a bulk transition. Therefore, the viscosity measurement (shear layer between rotor and stator) is representative of the entire fuel. However, the additized fuel had a definitive gradient, with the crystals selectively settling to the bottom of the stator, while the fuel above the rotor was clear. Visual inspection revealed minimal crystal suspension in the shear layer. The variation for the additized fuel is further illustrated in Figure 28, which shows the viscosity measurements at $-52.9\text{ }^{\circ}\text{C}$. Formation and settling of large crystals for the additized fuel is intensified, with a clear interface between the crystal and liquid layers at the bottom of the stator. The absolute effect of crystal formation on the viscosity measurements is not readily known, as the measurement is made in the shear layer of the fluid with minimal crystal presence. However, the shear viscosity primarily measures the fluid friction, or resistance to flow, between the liquid layers. Suspended solids can increase the inertial forces required for local flow, but it is believed they will not strongly impact the bulk fuel viscosity measurements reported herein.

Preliminary evaluation of the effect of the LT additive on the rotational viscosity results was performed by directly measuring the kinematic viscosity of Jet A (POSF-2926) with $2,000\text{ mg/L}$ LT additive using a Cannon-Fenske Routine Viscometer Tube (Size 100) at -40 to $-49\text{ }^{\circ}\text{C}$. There was excellent agreement between the rotational and tube viscosity measurements for temperatures above the fuel cloud point. For measurements made at -47 and $-49\text{ }^{\circ}\text{C}$ (below the viscosity knee), there was less than 5% absolute difference in the dynamic viscosity values. Therefore, it is believed that the rotational viscosities measurements performed in this study accurately represent the bulk fluid viscosity of the fluid, even with the presence of fuel crystals. Additional studies would provide improved insight and data for statistical verification.

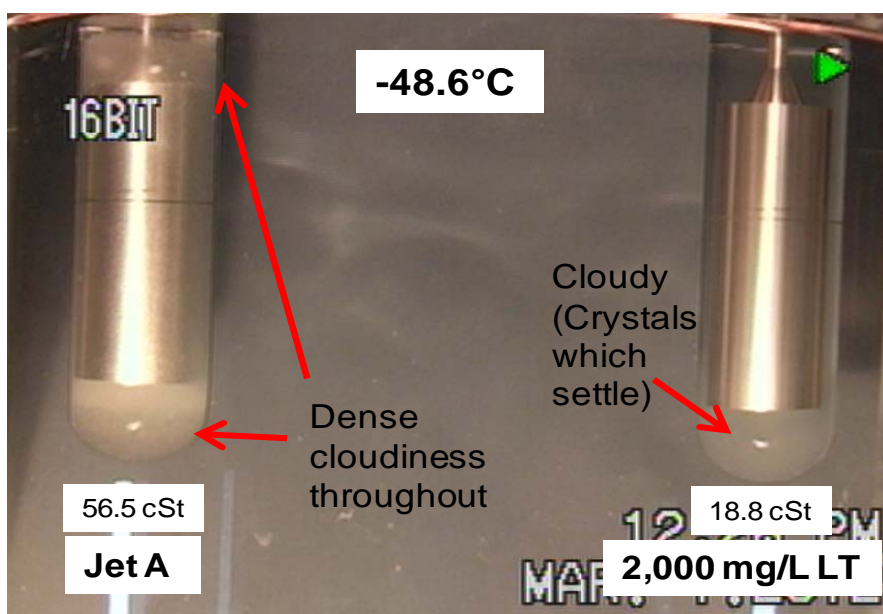


Figure 27. Images of scanning viscometer rotor/stators for measurement with Jet A (POSF-2926 – left) and Jet A with $2,000\text{ mg/L}$ LT additive (right) at $-48.6\text{ }^{\circ}\text{C}$

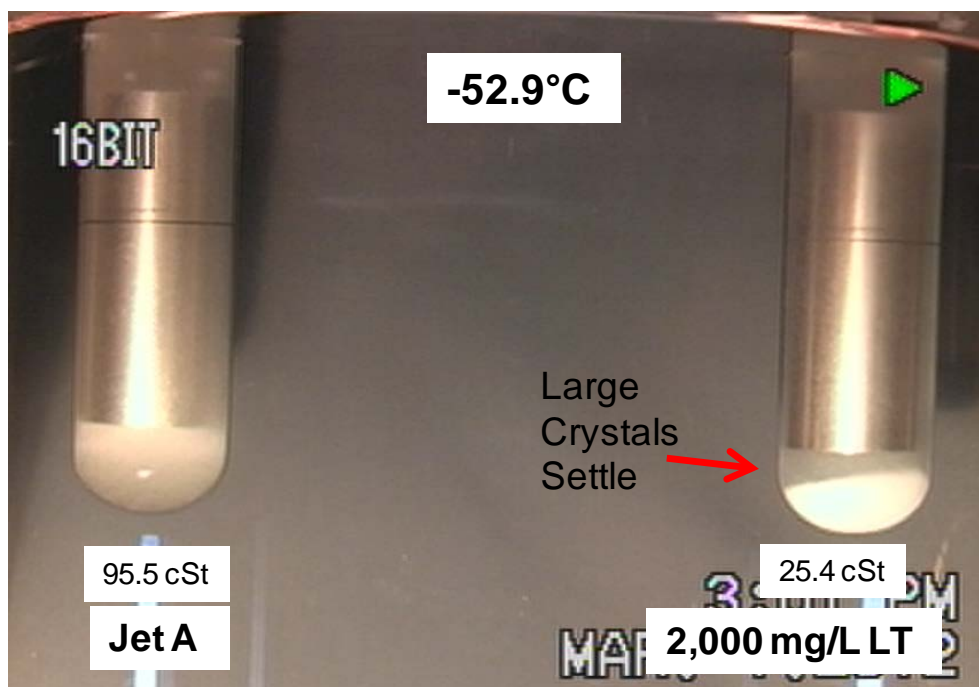


Figure 28. Images of scanning viscometer rotor/stators for measurement with Jet A (POSF-2926 – left) and Jet A with 2,000 mg/L LT additive (right) at -52.9°C

4.0 CONCLUSION

The use of the low temperature flowability improving additive (LT) developed in the JP-8+100 LT program was studied for use in Jet A fuels. One major goal of the current program was to determine if this low temperature additive can be employed in Jet A fuel (with a specification freeze point of -40°C) to improve the low temperature flowability to be equivalent to the flowability of JP-8 fuel (with a specification freeze point of -47°C). The program commenced in November 2010, and this final report covers the period November 2010 to June 2012. The results indicate the LT additive does improve the flowability of near specification maximum freeze point Jet A fuels (F.P. near -40°C) when employed at a concentration of 2,000 mg/L to a flowability equivalent to near specification maximum freeze point JP-8 fuels (F.P. near -47°C). The additive increases flowability not by changing the fuel freeze point, but rather by allowing the fuel to remain flowable by preventing the formation of large crystals which form a matrix which entraps the mostly liquid fuel. Viscosity measurements demonstrated that the LT additive increases the fuel viscosity at temperatures above incipient fuel crystallization, where the fuel remains a liquid. This viscosity increase is likely due to the large, high molecular weight oligomeric structure of the additive. Jet A fuels exhibit higher average low temperature liquid-phase viscosity than JP-8 fuels and the further increase due to the LT additive can place some Jet A fuel viscosities above the low temperature viscosity guidelines for proper nozzle atomization used by engine OEM's. It is recommended that further work be performed before the LT additive is fielded for use in Jet A fuel. In particular, the effect of the increased fuel viscosity at liquid fuel temperatures needs to be evaluated in the particular aircraft/engine platform being employed. The effect of this increased viscosity on fuel atomization in the engine combustor is likely dependent on the engine employed and the fuel flow schedule of the aircraft. In addition, observations of combustor liner coking at high additive concentrations during the previous U-2 and Global Hawk studies, emphasizes the need for combustor testing of the additive at the optimized use concentration in the engine system of interest. Thus, identification of the aircraft system or systems for which the LT additive may be required for operation with Jet A fuel is needed.

5.0 REFERENCES

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ACRONYM	DESCRIPTION
FSII	Fuel System Icing Inhibitor
JFTOT	
LT	Low Temperature
OEM	
QCM	Quartz Crystal Microbalance
SSIS	Small-Scale Icing Simulator
UDRI	University of Dayton Research Institute
WSIM	